MOTORI PASSO-PASSO

TEORIA E APPLICAZIONE

St ping Motor Systems 44
.... 44
for Stepping Motors 47
.... 47
.... 48
.... 48
.... 48
t 48
.... 49
.... 50
or ystems 52
ive for Milling Machines 52
rec ion Positioning of
.... 54
.... 55
ecorder 56
.... 56
.... 56
........KI.M.A.T.E.S. . (S.I.G.M.A.) 58

INTRODUCTION

This manual is written for the purpose of acquainting users with the important characteristics of permanent magnet stepping motor systems including logic, electronic drives, and motors. It is hoped that this summary may be of value to the designer charged with the responsibility of digital motion control

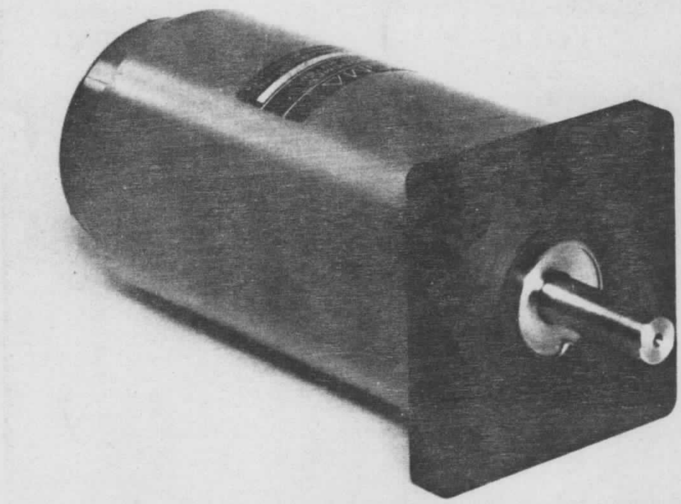
Stepping motor systems are gaining rapidly in importance for two reasons:

1. Commands, controls and data are more and more in digital form, since digital information is readily manipulated inexpensively with integrated circuits. Thus, when an output motion is desired, a digital device (the stepping motor) provides a logical link between digital information and mechanical translation.
2. The stepping motor is an inherently reliable device since its only mechanical connections are bearings and the output shaft. Therefore, in many applications, a stepping motor system can replace shorter-lived devices such as brakes and clutches with a considerable gain in over-all reliability.

In addition, more powerful stepping motors and more sophisticated driving techniques have extended the range of applications of stepping motors into areas of power and speed formerly unattainable to them.

TYPES OF STEPPING MOTORS

There are three broad classes of stepping motors available today – permanent magnet, variable reluctance and hybrids. This manual is concerned primarily with the permanent magnet motor, but it is appropriate to review the general characteristics of each distinct type.



Sigma Model 20-4288D200 Motor.

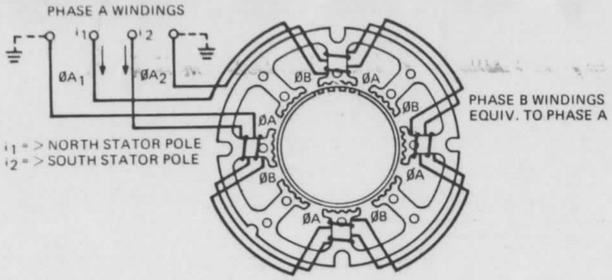


Figure 1. Permanent Magnet Motor, Axially Charged Sigma Series 20 Motor.

Permanent Magnet Motors

The permanent magnet (PM) motor contains a stator which has a number of wound poles. Each pole may have a number of teeth as part of its flux distributing member. The rotor is cylindrical and toothed.

The distinguishing feature of the PM motor is the incorporation of a permanent magnet in the magnetic circuit. Most PM motors add the permanent magnet in the rotor assembly. This magnet can be axially charged as in the Sigma Series 20 motors (Figure 1) or radially charged as in the small-size Sigma 18 motors (Figure 2).

The PM stepping motor operates by means of the interactions between the rotor magnet biasing flux and the magnetomotive forces generated by applied current in the stator windings. If the pattern of winding energization is fixed, there is a series of stable equilibrium points generated around the motor. The rotor will move to the nearest of these and remain there. If then the windings are excited in sequence, the rotor will follow the changing point of equilibrium and rotate in response to the changing pattern.

By virtue of the permanent magnet, there is a "detent" torque developed in the motor even when stator windings are not excited. A restoring torque

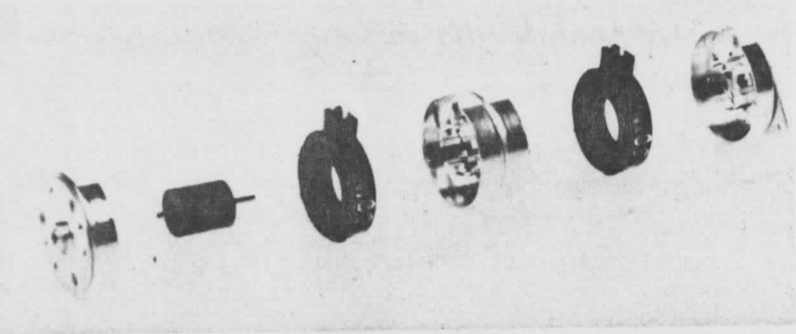


Figure 2. Permanent Magnet Motor, Radially Charged Sigma Series 18 Motor.

is generated on the rotor whenever the rotor is moved from the position which has minimum reluctance for the permanent magnet flux. This torque is much weaker than the energized torque, typically a few percent of the maximum torque.

The Sigma Series 9, a permanent magnet motor, has a completely different construction (Figure 3). This motor features very high static detent torque (nearly equal to holding torque) and extreme simplicity of drive. The stator has a permanent magnet, and the method of operation is such that there is no inherent reversibility, so that a reversible motor consists essentially of two separate devices on a single shaft.

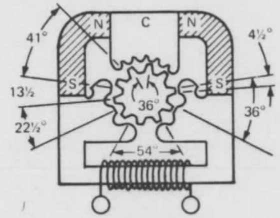


Figure 3. Permanent Magnet Motor, High Static Detent Torque, Sigma Series 9 Motors.

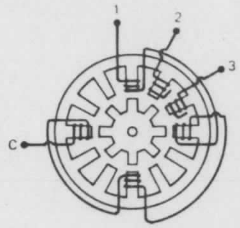


Figure 4. Variable Reluctance Motor. 15° VR Stepper (3-phase), complete winding shown one phase only.

Variable Reluctance Motors

A variable reluctance (VR) motor has a stator which has a number of wound poles. The rotor consists of a cylindrical, toothed member whose teeth have a relationship to the stator poles and their teeth (if any) determined by the step angle required. Figure 4 shows an example of typical motors of this type.

When a current is passed through the proper windings, a torque is developed in such a way as to turn the rotor to a position of minimum magnetic path reluctance. This position is stable statically in that external torque is required to move the rotor from this position. This position is not an "absolute" position in that there are many such stable points in the average motor. When a different set of windings is energized, the minimum reluctance point is at a different set of poles and rotor teeth, causing the rotor to move to a new position. By proper selection of the energizing sequence, these stable positions can be made to rotate smoothly around the stator poles, giving rise to a rotational speed at the rotor. When the energization sequence becomes fixed, the rotor position becomes fixed. Thus, the shaft position is "stepped" by changing the pattern of winding energization.

In a VR motor, the rotor teeth have little residual magnetism, as is found in the permanent magnet motor, so there is no force on the rotor (detent torque) when the stator is not energized. The VR motor operates in the same way as an AC electromagnet, in which magnetic attraction occurs regardless of the direction of the magnetic flux.

Hybrid Motors

There are a number of other devices which convert electrical pulse trains, or energization patterns, to motion. There are such devices as linear PM or VR stepping motors. Their operation is approximately the same except that the magnetic paths are in a linear dimension.

Another approach to stepping motor design is to provide internal torque amplification of an electrical stepping motor. One approach is to use internal gearing and reduce the step angle (no power gain). A second method is to "follow" the low power, low torque stepper with a linear power amplifier.

For torque amplification without power gain, the motor consists essentially of a stepping motor with a relatively large step angle and a gear system integral with the motor. A so-called harmonic drive is used which features a very large gear reduction by means of a flexing mechanical spline. This motor delivers a small stepping angle, typically 0.18 to 0.45 degrees, and may be useful in those applications where such small step angles are desired. The motor has fairly good speed and torque capabilities and reliability within the framework of its mechanical components.

For power amplification, a relatively small stepping motor may be used in conjunction with a hydraulic amplifier. Here, the stepping motor is used to drive the command control device in the hydraulic motor. Where the cost of the system and its associated hydraulic supply can be justified, the power gain can be considerable. Hybrid motors of this type can be obtained in the several horsepower range.

Summary–Comparison

In general, permanent magnet (PM) motors (as compared to VR motors) are more efficient, have better damping characteristics, and are available in higher power models. VR motors are simpler in construction, have low rotor inertia and, when lightly loaded, have high speed capability.

General Summary

	Permanent Magnet	Variable Reluctance	Hybrids	
Characteristic	(PM)	(VR)	Torque Amplified	Power Amplified
Efficiency	High	Low	Low	Med-High
Rotor Inertia	High	Low	Low	Low
Speed	Fairly High	High (limited loads)	Fairly Low	High
Damping	Good	Poor	Poor	Good
Power Output	High	Low	Low	Very High
Typical Step Angle	1.8°, 2.5°, 15°, 30°	7.5°, 15°, 30°	0.18°, 0.45°	1.5°, 2.25°

The foregoing summary may not be completely accurate in detail, but it does represent a reasonable approximation of the situation. The remainder of the material in this manual is applicable to permanent magnet motors, and may or may not be relevant to VR units.

CHARACTERISTICS OF PERMANENT MAGNET STEPPERS

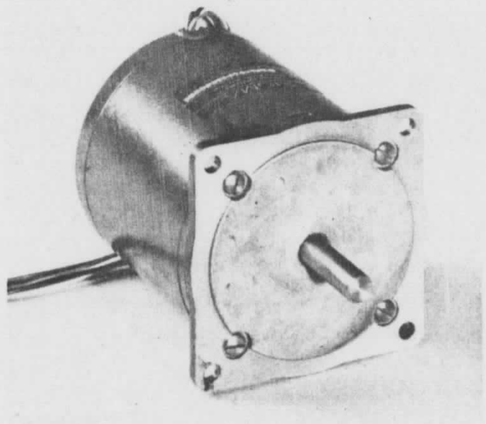
In presenting the characteristics of stepping motors, it must be emphasized that the motor is, in a sense, a transfer device between the electrical information presented by the driver and the mechanical motion delivered to the load. The actual functioning of the stepping motor system is heavily dependent upon the load and the driver, and both of these must be clearly specified if performance with a given stepping motor is to be predicted successfully. Obviously, it is not practical to generate performance data for every possible driver and load combination. Further, many systems defy characterization as a load that can be analyzed readily. The most practical approach under these circumstances is for the designer to acquaint himself with the general parameters and problems involved, make a reasonable choice of driver and motor, and then thoroughly test the combination in the actual system. This approach, used in conjunction with application engineering support from the stepping motor manufacturer, has proven considerably more useful than attempts to thoroughly quantify and analyze dynamic systems which rapidly become highly complex.

Single Step Motion

When a stepping motor takes a single step, due to appropriate excitation of its stator winding, the rotor translates to a new position. Detailed examination of the dynamic and static characteristics of such a step is useful to the understanding of correct application of stepping motors.

Dynamics of a Single Step Motion

The motion of the stepping motor rotor in the single-step mode resembles that of a torsional pendulum. Excitation is supplied by the stator flux, and the current rate of rise determines the maximum kinetic energy input to the rotor. Load friction is manifested as damping, while the system inertia consists of the sum of the rotor and load inertias. The effects of variation



Sigma Model 20-3437 D200 Motor.

of friction are shown in Figure 5a, in which the friction load is varied. Note that the rotor position as a function of time varies from underdamped to critically damped to overdamped as the friction load increases. Increasing inertia lowers the frequency of rotor oscillation (Figure 5b), while increased current rate of rise increases the magnitude of oscillation (Figure 5c). Clearly, both the magnitude of oscillation and the settling time are extremely important in most applications in that they also determine the ability of a system to restart or reverse after a stop has occurred. Various means of dealing with these effects are discussed on page 14.

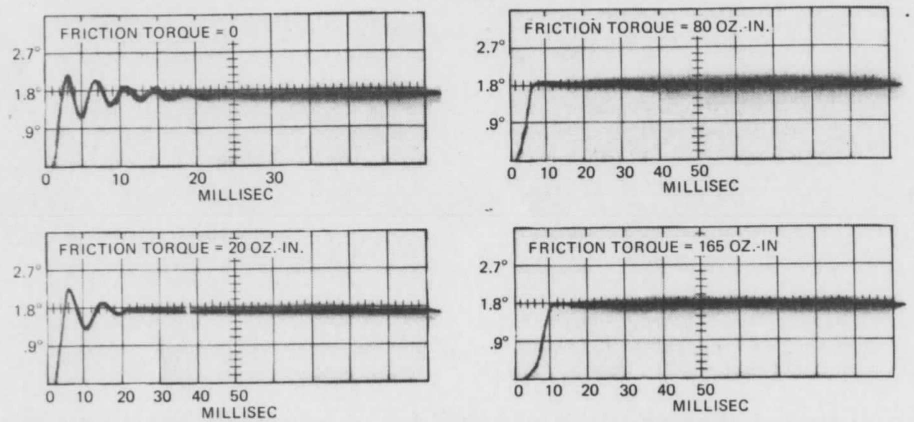


Figure 5a. Effect of Friction in Single Step Response, no external inertia. Test Condition: Sigma Model 20-3437D200-F0.75 Motor with Unipolar R/L Drive ($R_S = 3\Omega$).

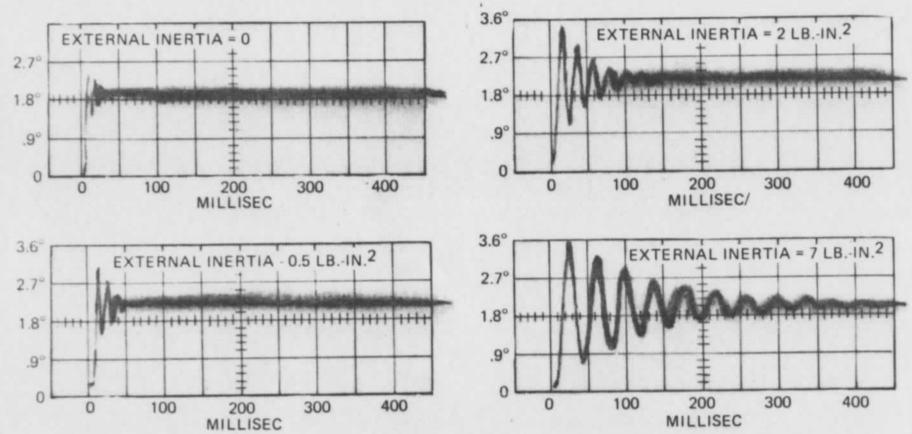


Figure 5b. Effect of Inertia on Single Step Response, no external friction. Test Condition: Sigma Model 20-3437D200-F0.75 Motor with Unipolar R/L Drive ($R_S = 3\Omega$).

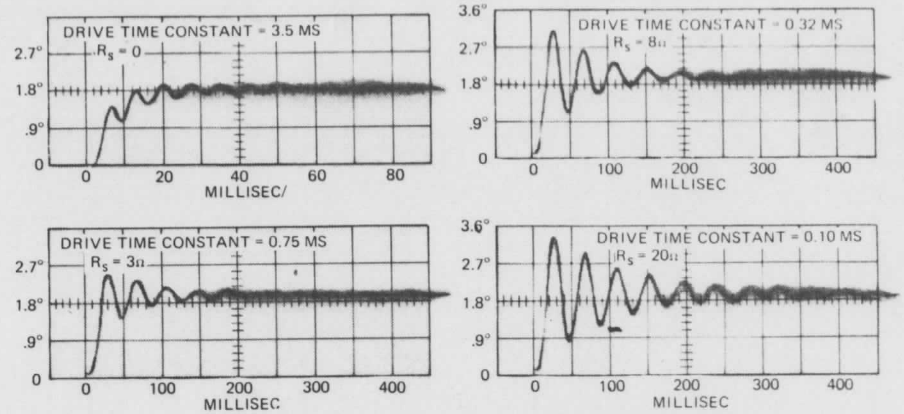


Figure 5c. Effect of Current Rise Time on Single Step Response, no external friction or inertia. Test Condition: Sigma Model 20-3437D200-F0.75 Motor with Unipolar R/L Drive.

Angular Accuracy

The accuracy of any particular step is rated at ±3% noncumulative for the Sigma Series 20 motors under no load conditions. For instance, in a Series 20 motor the step angle is 1.8° or $108'$; if 1 step is taken from a reference position the final angle of the rotor will be $108' \pm 3.24'$. If 1000 steps are taken, the angular motion of the shaft will be $108{,}000' \pm 3.24'$ – corresponding to five complete revolutions of the output shaft. The point is, of course, that the rated angular error (in this case $\pm 3.24'$) is the same regardless of the number of steps taken. The actual measured error is apt to be considerably less than the rated value. This high order of accuracy results because of the inherently symmetrical construction and the magnetic averaging over many poles that is characteristic of stepping motors.

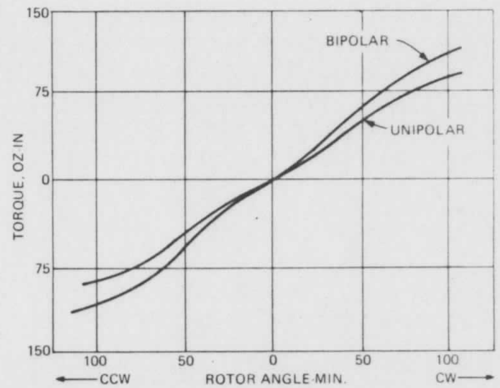


Figure 6a. Torque-Displacement Curve. Test Motor: Sigma Model 20-3424D200-F1.8

Nevertheless, where accuracy is critical, the designer must be alert to certain application problems. Ordinarily, these are traceable to two basic causes – choice of a motor with insufficient stiffness, and winding current balance.

resistenza a flessione

Stiffness refers to the torque-displacement curve that is generated when the rotor is deflected from its energized rest position (Figure 6a). The significance of the curve is that the rotor rest position will be such as to balance the load torque – i.e., the rotor will not be at its unloaded position, but at a different point. This effect theoretically would not inherently affect the step-to-step angular motion, but two problems arise. First, load torque may actually vary somewhat from step to step, so that the real position between steps may be in error by corresponding amounts. Second, the system dynamics may change enough so that the step overshoot, and the direction from which the final position is approached, may change, with deleterious effects on measured angular accuracy.

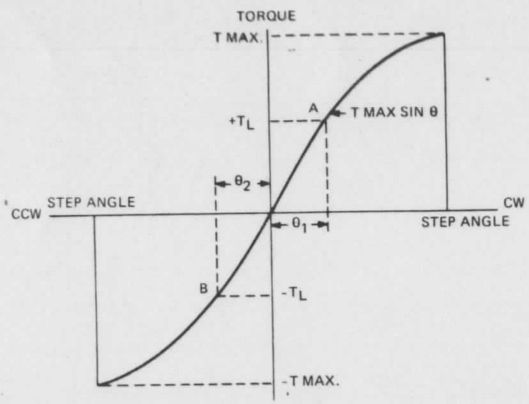


Figure 6b. Position Errors caused by Load Torque.

For example, if a system has a torque-angle curve as shown in Figure 6b and a static friction load of T_L, for clockwise rotation, the static position at the end of a step is not at the origin as drawn but rather at point A. The presence of T_L generates an error θ in the ccw direction, where $\theta_1 \approx \mathrm{Sin}^{-1}(T_L/T_{max})$. If the direction of rotation were always clockwise, and T_L were constant, θ_1 would never be observed. However, if the origin were also approached from the counterclockwise direction, the final equilibrium point would be at B, with a clockwise error of θ_2, equal to θ_1. Therefore, the effective error in position observed is equal to $2\ \mathrm{Sin}^{-1}(T_L/T_{max})$.

The effect of system dynamics on this potential error is dramatic. Rotor overshoot (underdamped system response) tends to allow the rotor to approach the origin closer than calculation might indicate, even on a static basis. One cause, of course, is the transfer of rotor kinetic energy to output work $(\theta_1 T_L)$; another cause is easier to visualize as "dither" which coaxes the static position closer to the origin.

vibratore

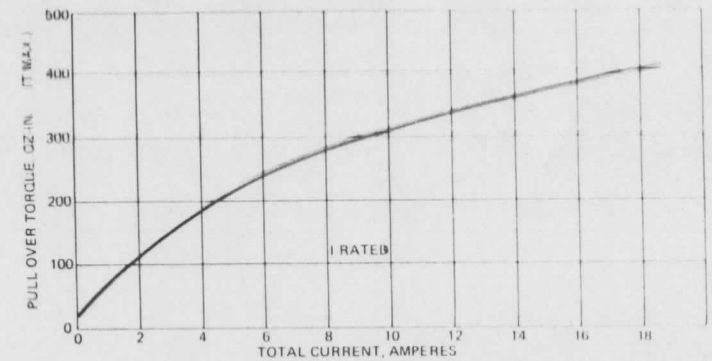
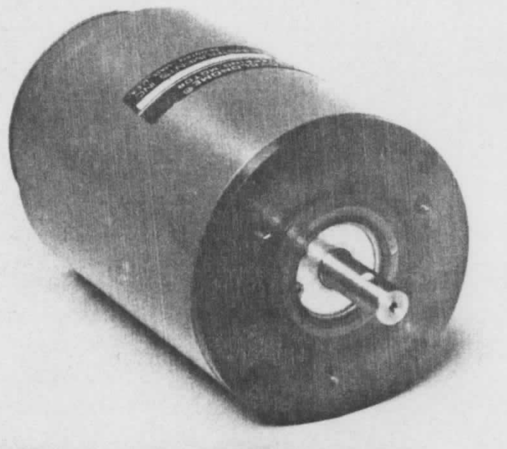


Figure 7. Torque-Current Curve. Test Condition: Sigma Model 20-3437D200-F0.75 Motor with Unipolar two phase drive.

Another factor in the final rotor rest position is the magnitude of the winding currents and the balance between the currents in the windings. In Figure 7, the relationship between *T*max and winding current is shown. Obviously, if the magnitude of the current in various windings is not constant, the stiffness will vary, affecting the error.

In many commonly used drive systems, two windings are energized simultaneously. If the current in one of these windings is reduced gradually to zero while the other remains fixed, the shaft will move ½ step, with the motion being related linearly to the winding current. Naturally, these factors must be considered in driver design if the highest angular accuracy is required. It should also be noted that the unenergized rotor rest position differs from the rest position with two windings energized by approximately one-half step.



Sigma Model 20–4266TD200 Motor.

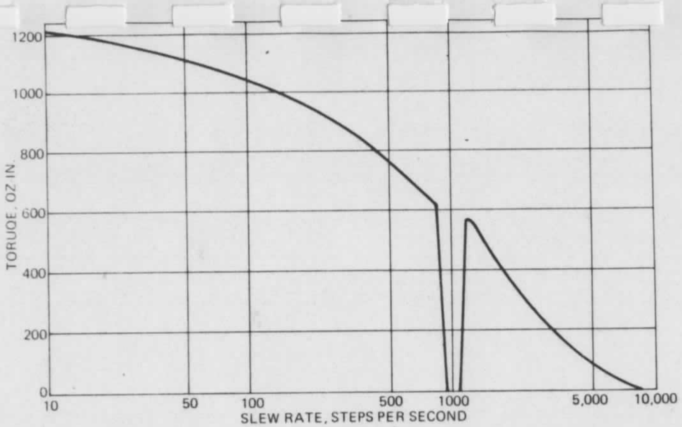


Figure 8. *Slew Curve. Test Condition: Sigma Model 20-4266TD200-F0.6 Motor with 65V Bipolar Chopper Drive. I_ϕ = 7.5 Amps, P_m = 34 Watts, J Ext. = 4 lb.-in.^{2}*

Multiple Step Motion

Stepping motor data is available in three main forms:

1. *Start-run (slew) curves.*
   The motor is run up to speed gradually, and a varying friction load is applied until the motor loses synchronism. The resulting data are plotted as a speed-torque curve (Figure 8).
2. *Start-stop curves.*
   Friction and inertial loads are applied to the motor at rest. A pulse burst containing a fixed number of pulses (say, 200 pulses for a 200 step/revolution motor) is used to drive the motor. The time period of the pulse train is long compared to the starting transients of the motor dynamic response. The frequency of the pulses is varied to determine the maximum frequency at which the given load can be both started and stopped without error. The three dimensional curve obtained is usually plotted as a family of inertia curves on a torque-speed plot (Figure 9). Generally, these data are combined on one plot.
3. *Ramping Curve for larger motors.*
   Fixed loads are again used on the motor at rest. A pulse train is applied containing a fixed number of pulses, but arranged so that the frequency starts at a low value, accelerates to a top speed, runs at top speed, decelerates to the low speed, and then stops. This type of operation is typical for large loads such as machine tools. The data are taken in much the same way as the start-stop curves, and are plotted as shown in Figure 10. Another set of curves (Figure 10a) shows the effect of varying ramp speeds (using a linear ramp), upon the amount of load that can be accelerated synchronously to a fixed speed. The effect of half-step drive is also plotted on this curve.

Slew-mode Data

Examination of slew-mode data on a stepping motor reveals several interesting points. First, as the current rate of rise in the windings is increased, the

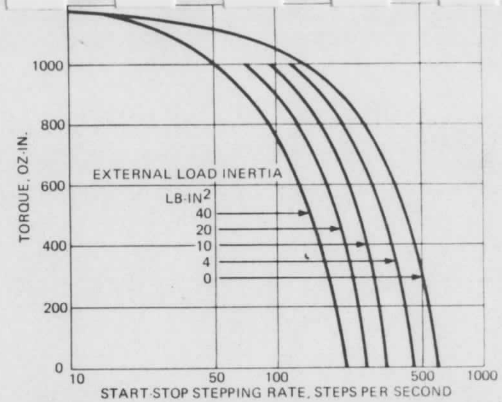


Figure 9. *Start-Stop Curves. Test Conditions: Sigma Model 20-4266TD-200-F0.6 with 65V Bipolar Chopper Drive. I_ϕ = 7.5 Amps, P_m = 34 Watts.*

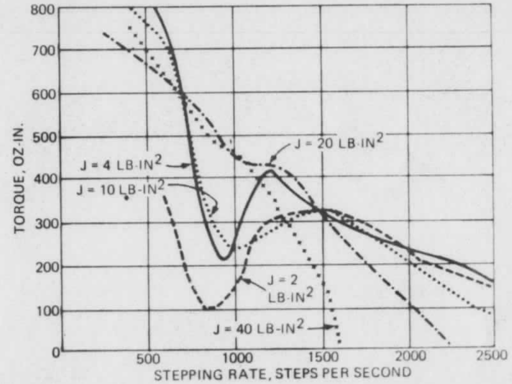


Figure 10. Ramping Characteristics. Test Condition: Sigma Model 20-4266D200-F0.6. 65V Bipolar Chopper, 7.5 Amp./ϕ. .3 Second Ramp.

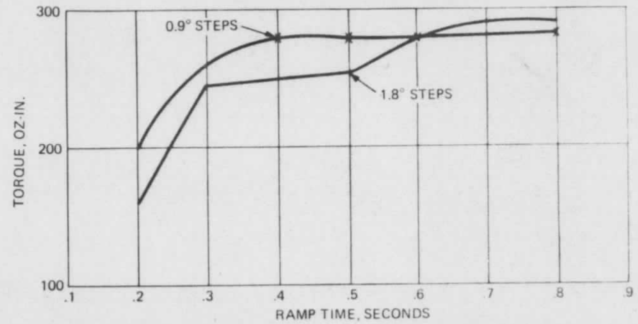


Figure 10a. Available Torque at 600 RPM vs. Ramping Speed. Test Condition: Sigma Model 20-4266D200-F0.6 Motor. I = 7.5 A/ϕ, 65V Bipolar Chopper, J = 4 lb.-in^2.

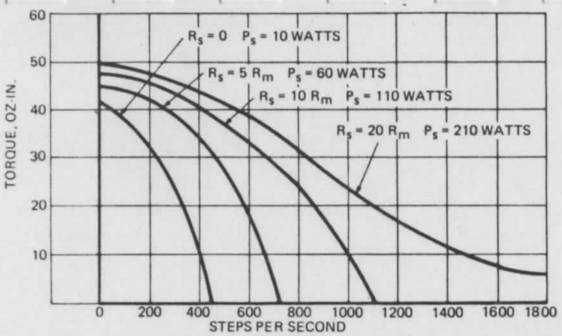


Figure 11. Slew Mode Data with Varying Current Rate of Rise. Test Condition: Sigma Model 20-2223D200-F1.4 Motor.

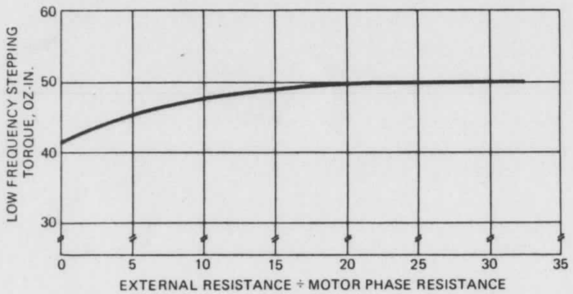


Figure 12. Slew Mode Data at Low Frequency. Test Condition: Sigma Model 20-2223D200-F1.4 Motor with Unipolar R/L Drive, -4 Resistor Circuit, P_m = 9 Watts, I_ϕ = 1.8 Amp.

high frequency torque available increases (Figure 11). This fact is of central importance in the design of drive circuits – the goal of most drive circuit design effort is to achieve high rate of rise of current in the motor windings while limiting steady-state current value to the motor (page 21.) Another phenomenon that is perhaps less expected is that the low frequency torque increases as the current rate of rise increases, as shown in Figure 12. This occurs simply because the rotor is in position to deliver maximum torque at the beginning of the step, and if the current in the windings rises rapidly enough to achieve its final value before the rotor can move appreciably, maximum peak torque will be delivered by the motor.

There is a fixed relationship between the maximum value of energized detent torque (T_{max} of Figures 6 and 7) or pull-over torque and the maximum load torque that can be stepped. Referring to Figure 13, assume the motor is loaded with a torque, T_L. This generates a rotor lag angle of θ_e as previously described. When the motor is commanded to take a step, the coordinates of the torque-displacement curve advance $\pi/2$ electrical degrees or 1 step (dashed curve). The lag angle θ_e causes a motor restoring torque T_1 (always less than the peak torque T_{max}). With this load, the net excess restoring torque is $T_1 - T_L$, which is positive, and the motor will complete the step.

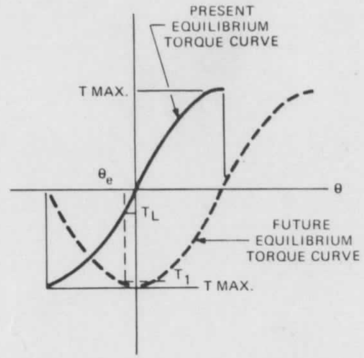


Figure 13. Maximum Stepping Torque of Motor, where available torque = $T_1 - T_L > 0$. Motor will step.

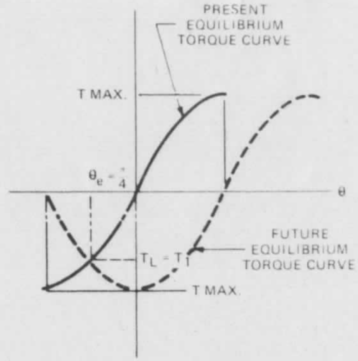


Figure 14. Maximum Stepping Torque of Motor, where available torque = $T_1 - T_L = 0$. Motor will not step.

If the system friction is enough to generate $\pi/4$ electrical degrees of error, the situation becomes that shown in Figure 14. In this case T_L is equal to $\sqrt{2}T_{max}/2$, since $T_L = T_{max} \sin\theta_e$. When the motor steps, the origin shifts $\pi/2$ degrees (dashed curve). The motor restoring torque is now $\sqrt{2}/2\ T_{max}$ which is equal to T_L; hence, in the limit the motor cannot step since the net restoring torque is zero.

If the load torque is greater than $\sqrt{2}/2 T_{max}$ (i.e., θ_e greater than $\pi/4$ in Figure 15) the motor restoring torque is less than the load torque and the motor cannot step.

Therefore, the maximum frictional load a motor can step is theoretically $\sqrt{2}/2$ times the maximum energized pull-over torque. The precision of this relationship is related to how closely the torque displacement curve can be

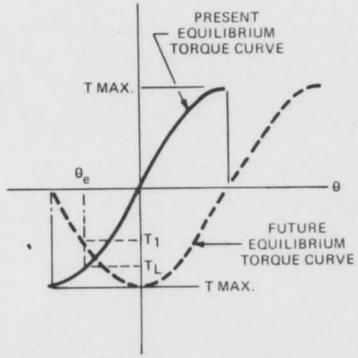
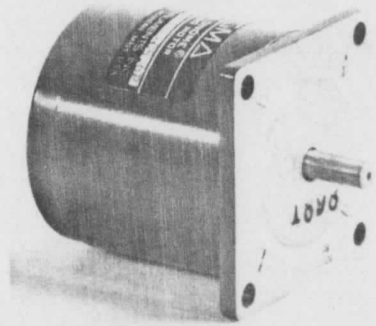


Figure 15. Maximum Stepping Torque of Motor, where available torque = $T_1 - T_L < 0$. Motor will not step.



Sigma Model
20-2223 D200 Motor.

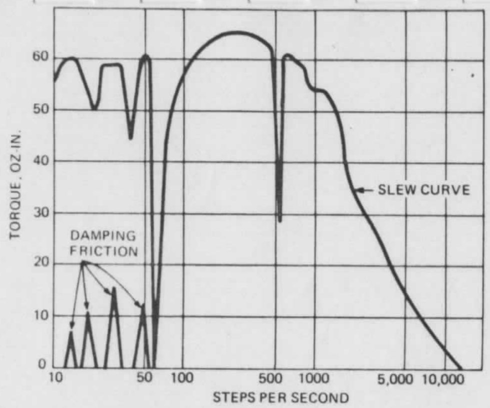


Figure 16. Damping Friction as aid to Stable Operation. Test Condition: Sigma Model 20-2223D200-F1.4 Motor with 35V two phase Chopper Drive. 1.8° Step, 9 Watts, 2.6 Amp/φ.

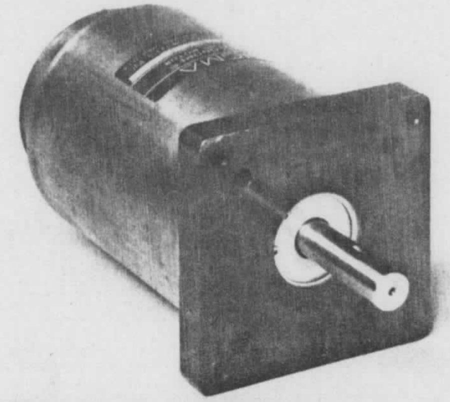
approximated by the expression: $T_L = T_{max} \text{ Sin } \theta_e$. It is usually a good approximation for the Sigma Series 18 and 20 motors.

Under conditions of high current rate of rise, careful control of pulse rate will disclose regions where the motor will not run at all without a torque load (20–150 Hz region on Figure 16). The friction required to achieve stable operation is plotted as the sharply peaked triangles at 30Hz, 50Hz, etc., on Figure 16. These regions are related to the resonant frequency of the rotor. If insufficient damping is present, the periodic excitation of the rotor at its resonant frequency, or a submultiple of it, will reinforce the resonance and cause the amplitude of the oscillation to increase. A high current rate of rise further accentuates this oscillation and will carry the rotor to a region such that the next pulse will drive it back instead of forward, and a dithering, unstable operating mode will result. Friction loads (Figure 5a) damp the rotor oscillation enough so that it will operate in these regions with no difficulty.

Another major resonance occurs in the 900–1200 Hz region where a loss in torque will be observed. It is basic to all permanent magnet steppers under conditions of high overdrive and is related to the phenomena that cause the appearance of "critical speeds" in large multi-horsepower synchronous motors. This resonance is reduced with heavy inertial loading, but at the cost of acceleration characteristics. In general, it is best to avoid operation in this region, or use one of the drive systems that reduce resonance effects (page 25).

Start-stop Mode

In many applications, the motor must start and stop under load, and without any acceleration and deceleration times. These requirements severely limit the top speeds available. As a typical example, a Sigma model 20–4270 can rotate synchronously in the range of 5000 to 8000 steps/second in the slew mode, but is limited to 300 to 800 steps/ second for synchronous start-stops. Start-stop operation with a variable number of



Sigma Model 20–4270TD200 Motor.

steps must be examined critically, since results achievable will depend to a considerable degree upon the number of steps taken, especially when the time period for the pulse train is short with respect to the rotor dynamic response time. This is due to the variation in the rotor-stator lag angle with number of steps, as illustrated in Figure 17. Since results will depend upon number of steps up to a total of about 15 steps, it is necessary to examine stepping characteristics carefully under these circumstances.

The amount of time required to settle the load varies with load and drive conditions, but it is frequently desirable to improve settling time characteristics. One method for accomplishing this that works well with fixed load conditions is reverse pulse damping. In this system, a reversing pulse of carefully selected duration is applied to the motor after the last pulse has been initiated (See Figures 18 and 19). Both the duration and the timing

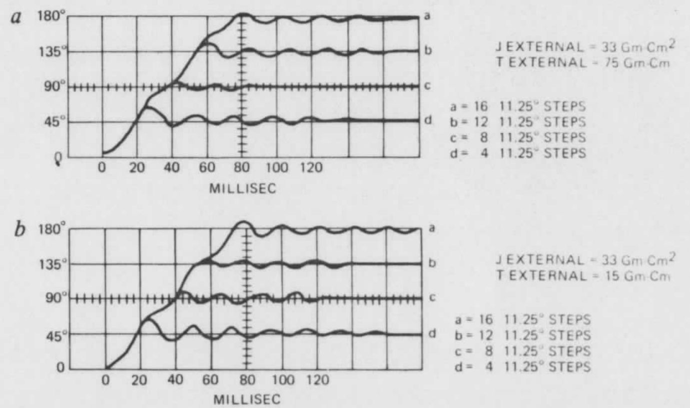


Figure 17. Position Response of Stepping Motor. Test Condition: Sigma Model 18-2013D32-21463 Motor with 30V Bipolar R/L, 20Ω Drive, 0.5 Amp/φ.

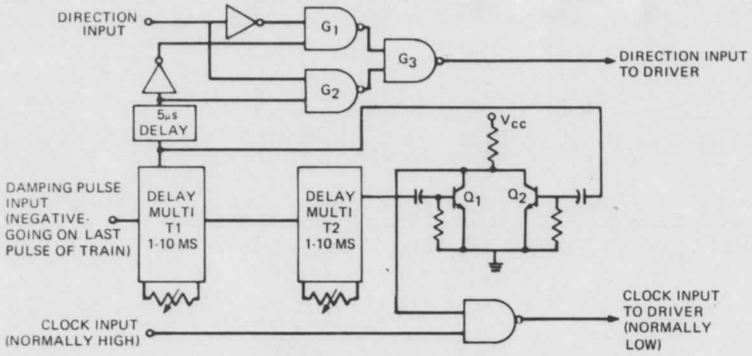


Figure 18. Reverse Pulse Damping Diagram.

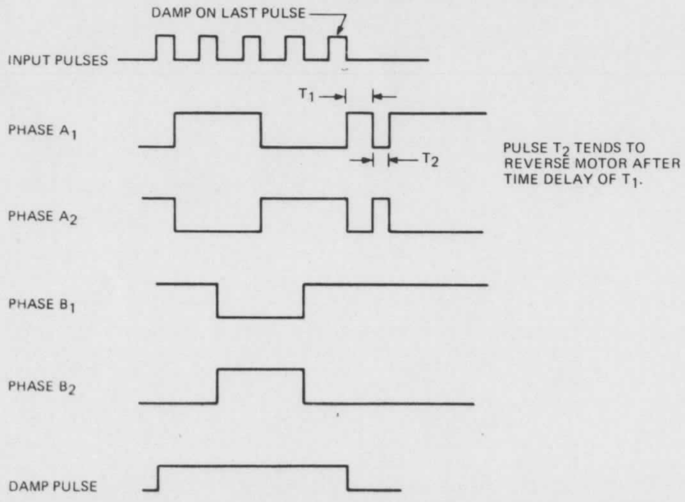


Figure 19. Current Wave forms for Reverse Pulse Damping.

of the damping pulse should be determined experimentally with normal load in place. Actual results of such damping are shown in Figures 20 and 21. It must be emphasized that the timing values for reverse pulse damping depend upon the load parameters, so that the system should be checked over the full range of variation of load characteristics.

Another aid in damping is a system such as current feeding (page 34) where the supply voltage varies with speed. In such a system, the voltage is low at low speeds and less excess kinetic energy is added to the rotor, which improves settling time considerably.

Restarting and Reversing

The ability of a stepping motor and driver system to restart or reverse at the end of a sequence of pulses is related to its settling time under the

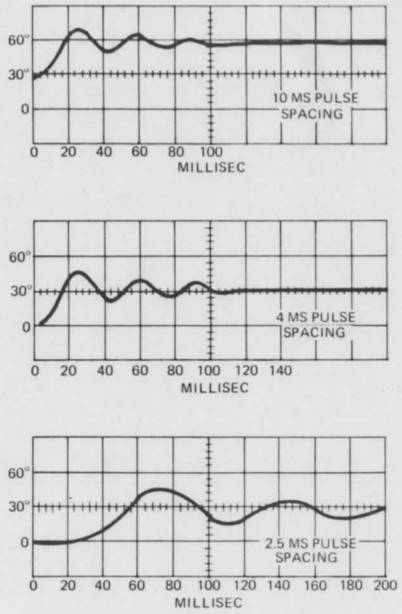


Figure 20. Double Pulse Response of Unloaded Motor, without Damping. Test Conditions: Sigma Model 19-2527 Motor with 35V Bipolar Chopper Drive.

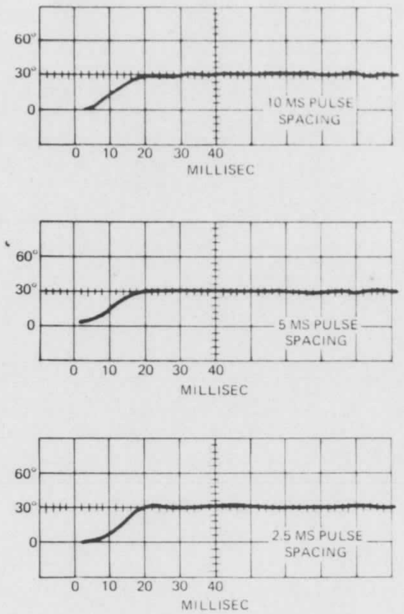


Figure 21. Double Pulse Response of Unloaded Motor, with Reverse Pulse Damping. Test Conditions: Sigma Model 19-2527 Motor with 35V Bipolar Chopper Drive.

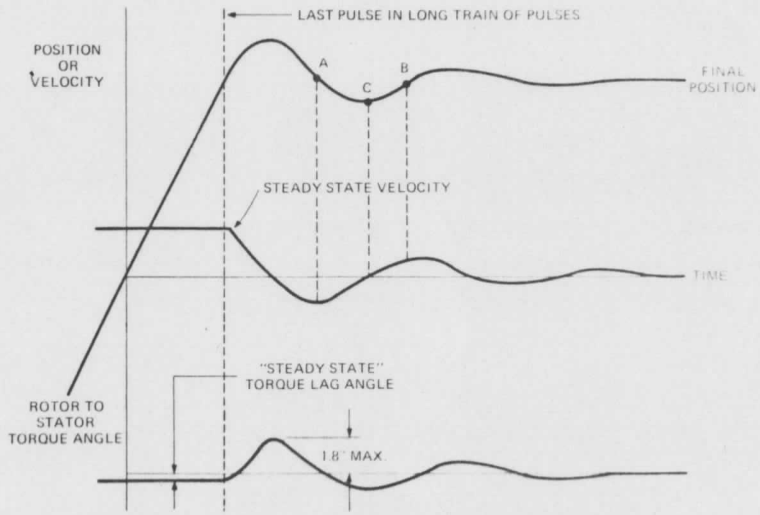


Figure 22. Transient Response at End of Pulse Train.

load in question. Consider Figure 22. At the end of a long train of pulses, the rotor will tend to overshoot the final position as indicated. The maximum value of the rotor lag angle can approach 1.8 degrees (Sigma Series 20 motors) under conditions of high overdrive, high inertial loading, or low system friction. It can be seen that there are discrete "windows" in time during which the motor cannot be restarted or reversed because the rotor velocity is too high or in the wrong direction, or both. Likewise, the rotor-stator angle can be improper for the generation of torque when the command for a step arrives, even if the rotor velocity is correct. For example, the motor can be reversed easily at point *A*, but it would probably not restart in the same direction because the velocity is a maximum in the wrong direction. Point *B* is satisfactory for restarting but not good for reversing. At *C*, the rotor is out of position for either restart or reverse.

Thus, it may be seen that the restart or reverse frequency is really not so much a question of frequency as it is a matter of time after the last pulse. If the point of restart is chosen optimally, the motor can be restarted at a higher speed than if the motor had been sitting still.

The ideal way to handle this situation is to have a way to measure shaft position or velocity to determine the restart or reverse timing. If this is impractical, the only alternative is to wait until the rotor settles after this last step. This is a question of damping and was discussed on page 14.

Ramping

In the ramping mode, the motor is accelerated and decelerated with fixed load applied. The ideal ramp would be generally exponential for acceleration and a reverse exponential for deceleration (Figure 23). The deceleration time constant can be 10% to 15% less than the acceleration time constant. In practice, a simple and widely used compromise is the quasi-linear ramp, one time constant of an exponential curve, which was used in obtaining data for this manual. In Figure 24a, a single ramp slope value, generally appropriate to the motor under test, was used. Figure 24b was generated with a typical inertial load of 4 lb $-\text{in}^2$. The data obtained in this manner are interesting in several respects. First, a certain amount of load inertia aids in running close to the resonance at 900 steps/second (Sigma Series 20

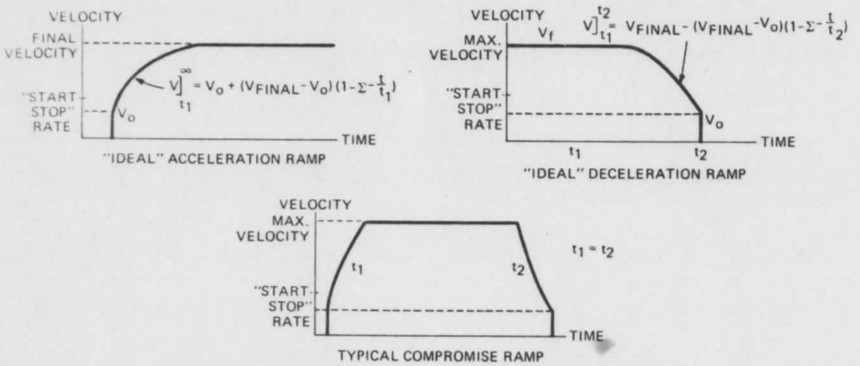


Figure 23. Accelration and Deceleration Ramps.

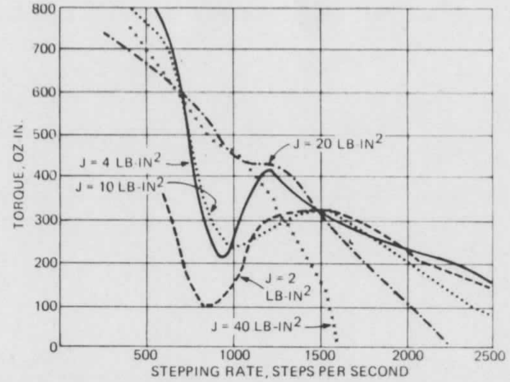


Figure 24a. Ramping Characteristics. Test Conditions: Sigma Model 20-4266D200-F0.6 Motor. 65V Bipolar Chopper, 7.5 A/ϕ, 0.3 Second Ramp.

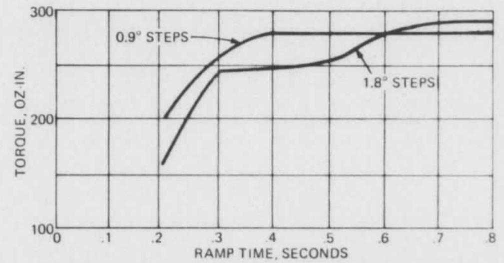


Figure 24b. Available Torque at 600 RPM vs. Ramping Speed. Test Conditions: Sigma Model 20-4266D200-F0.6 Motor. $I = 7.5\ A/\phi$, 65V Bipolar Chopper, $J = 4$ lb.-in.^{2}.

motors). Since the motor must start/stop at a given low frequency (in this case $f_{LO} \approx 100$ steps per second), increasing inertia limits the frequency of operation (See Figure 9). The half-step drive (discussed on page 25) aids performance where resonance is a limiting factor, but is somewhat inferior in low frequency torque compared to the full-step drive.

In order to accurately predict stepping motor system performance under ramping conditions, four sets of data are required using the exact driver anticipated.

The slew curve, Figure 8, indicates the maximum torque that is available from the motor-driver combination in the limiting "steady-state" condition after all start-up transients are over. Figure 9 can be used to predict the maximum frequency at which the load can be started or stopped synchronously with acceleration and deceleration.

In themselves, these curves will not fully predict performance when the motor is accelerated and decelerated. Figure 24a shows the frictional and

inertial load capabilities of a motor as a function of maximum top speed with a fixed 0.3 second linear ramp. Figure 24b shows the effect of ramp time on the available frictional torque capability of the motor. To show this, the inertial load was held constant at 4 lb–in^2.

Therefore, when examining an application, an important consideration must be kept in mind. The torque available for driving frictional loads during ramping is always less than indicated by the slew curves.

The first reason is straightforward. The torque required to accelerate the rotor and load inertia is given by the well-known equation:

$$Ta = (I_{\text{Load}} + I_{\text{rotor}})\,\alpha$$

Therefore, one might expect the torque available for frictional loads would be the difference between the torque shown at the desired frequency on the slew curve and the torque required for inertial acceleration, given above. As a matter of fact, because the system is accelerating and because of the torque dip at the resonance point at 1 KHz, the actual torque available is less, as indicated in Figure 24a. Thus, as the acceleration becomes higher, i.e., shorter ramps, the available torque becomes significantly less than the previous calculation indicates. This additional reduction is caused by the fact that during acceleration, the rotor-stator lag angle is greater than the angle at steady-state conditions. This additional lag causes loss of torque as discussed previously (Figure 6b).

Specifically, for an 0.3 second ramp, a 2000 step per second top speed, a 100 step per second starting speed, and a 4 lb–in^2 load, the torque values are indicated in the table below:

Slew Curve Torque at 2KC (Figure 8)	350 oz-in
Acceleration Torque required ($T = I\alpha$)	50 oz-in
Expected Available Torque	300 oz-in
Actual Available Torque (Figure 24a or 24b)	240 oz–in
Loss caused by rotor lag	60 oz–in

Figure 24b also shows the effect on torque of the resonance control created by half-step drive. For ramp times less than 0.6 seconds, half-step drive delivers more torque than full-step drive. With longer ramp times, that is approaching "steady-state," full-step drive delivers more torque because of its higher magnetic efficiency.

In conclusion, the acceleration performance of a stepping motor is a complex function of driver, load friction and inertia, ramp time, starting frequency and final frequency. No theoretical models are available at this time which will predict the behavior of a system. Trial and error methods are the only practical solution.

DRIVE CIRCUITS

Drive circuit design is one of the most important aspects of a stepping motor system. The overall system performance is heavily dependent upon the drive system, not only in available power delivered to the load, but also in such parameters as efficiency, power dissipation and cost.

A stepping motor drive system, diagrammed in Figure 25, accepts a drive signal and converts it to the proper format for driving the motor windings. A power amplifier drives the required current through the windings, and a power return system removes the current from the windings at the termination of the step.

State Generation

As previously discussed, the motor rotates in response to a changing pattern of interactions between the rotor magnetic field and the stator magnetic fields. The function of the State Generator is to create the proper sequence and pattern of states in response to a serial pulse train.

There are two major sequences which will cause the motor to step. One is called a "wave" drive, in which only one set of stator poles are energized at a time (Figure 1). The other sequence energizes both pole sets simultaneously and is called "two-phase" drive. Either of these will cause an $N°$ per step motor to step by increments of $N°$, but there is an $N°/2$ spatial displacement of the stator and rotor between the two sequences. The idealized tooth alignments are shown in Figures 26a and b.

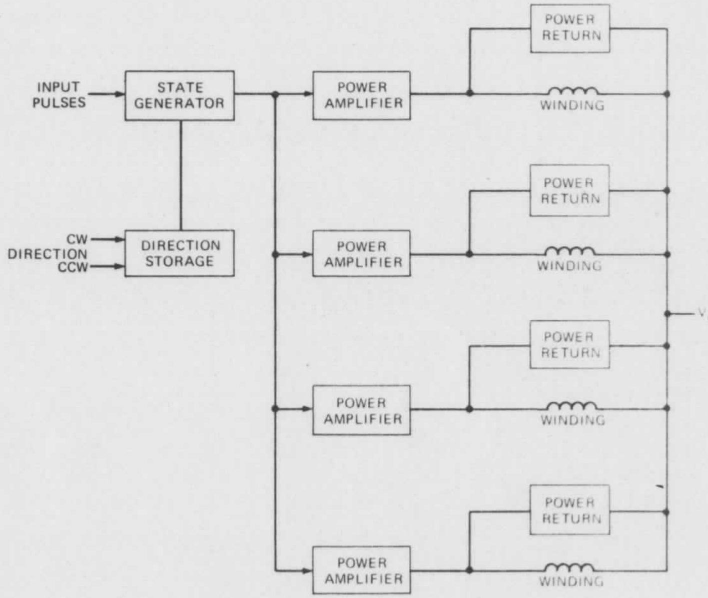


Figure 25. Block Diagram of Motor Driver.

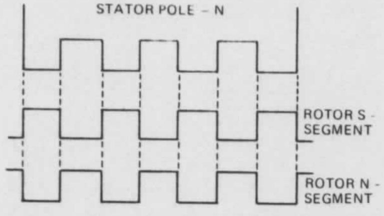


Figure 26a. Idealized Tooth Alignments for Wave Drive.

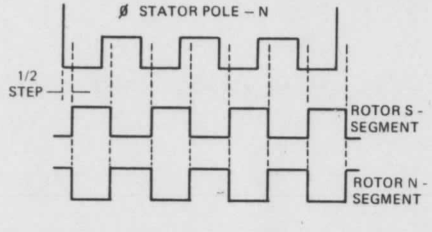


Figure 26b. Idealized Tooth Alignments for Two-Phase Drive.

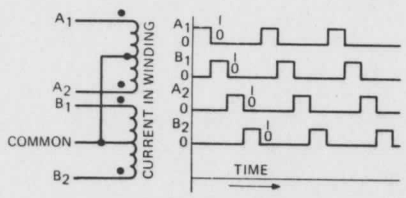


Figure 27. Unipolar Wave Drive.

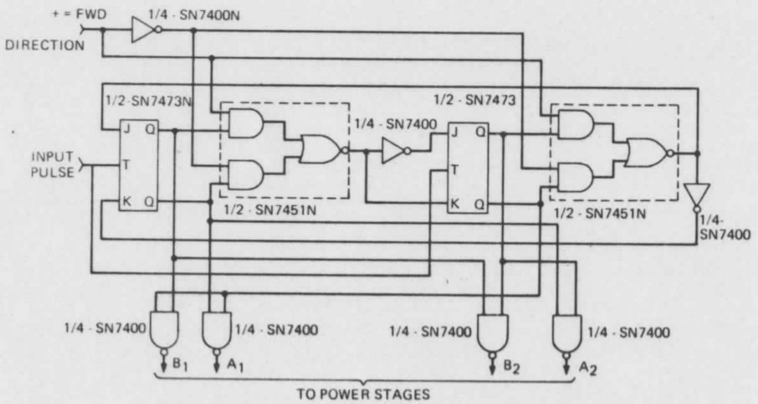


Figure 28. State Generator for Wave Excitation.

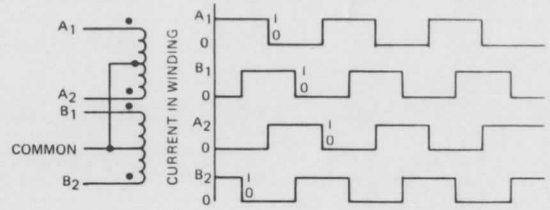


Figure 29. Unipolar Two Phase Drive.

Wave Drive

In this sequence, the required currents are shown in Figure 27. The A_1 current energizes all phase A poles in Figure 1 to create a North pole at the stator pole teeth. Current B_1 then generates a North pole at the phase B pole teeth. Similarly, the A_2 current generates a South pole at the pole A teeth. Finally, B_2 creates a South pole on the B phase poles. During this sequence, the rotor advances to align the rotor and stator teeth. The logic required to generate these waveforms is shown in Figure 28.

Two-phase Drive

Although the wave drive is a perfectly valid stepping sequence, it is not the preferred sequence for two-phase stepping motors of the type manufactured by Sigma. It can be shown that the ampere-turns on the stator poles per watt of input power are 41% higher if both of the $\emptyset A$ and $\emptyset B$ poles are driven. This is done by driving the four windings A_1, A_2, B_1 and B_2 two at a time. However, the torque does not match this increase of 41%. Although torque per ampere-turn is higher for the wave drive tooth alignment (Figure 26a), nonetheless, there is a net gain in torque per watt of about 20% for the two-phase alignment. (See also page 30).

The sequence of phase currents is shown in Figure 29. Current in A_1 generates a North pole in the A stator poles, while current in A_2 generates a South pole. Likewise B_1 currents create a North pole in the B stator

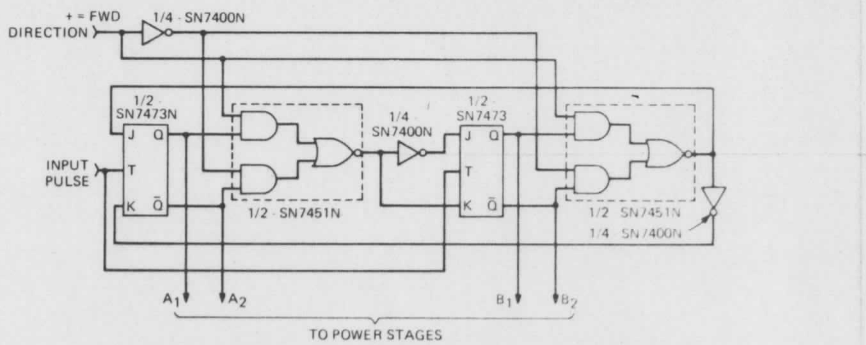


Figure 30. State Generator for Two Phase Excitation.

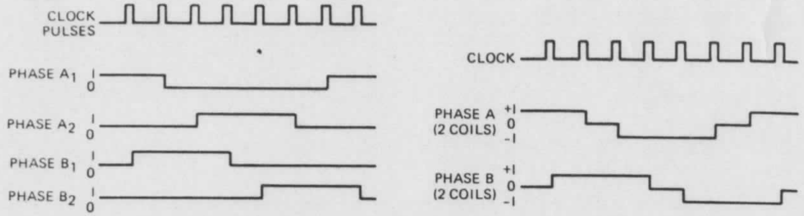


Figure 31. Half Step Drive. A. Phase Current for Unipolar Half-Step Drive. B. Phase Current for Bipolar Half-Step Drive.

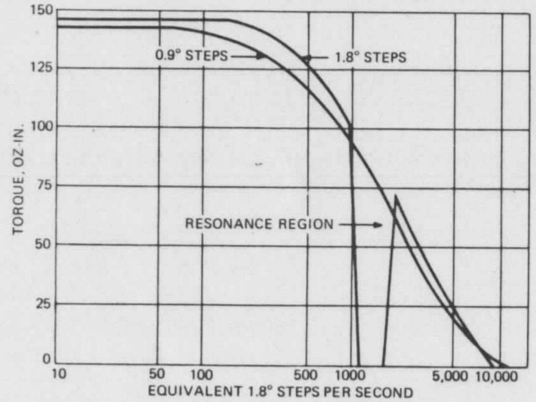


Figure 32. Half Step vs. Full Step Drive, Slew Curve Comparison. Test Conditions: Sigma Model 20-3424D200-F1.8 Motor with 35V Bipolar Chopper Drive. 10 Watts Max., 2.8 Amp/φ, 5 Watts Min. Constant Current per Phase.

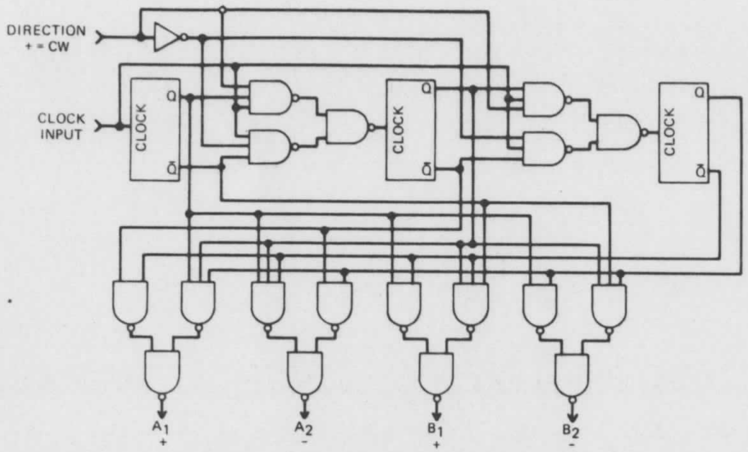


Figure 33. Half-Step Logic Diagram.

poles and B_2 creates South poles. All four combinations of current in two windings at the time are generated and give rise to four motor steps. The pattern repeats every four steps. The logic is shown in Figure 30. Note that the logic is slightly simpler than the wave drive. For this reason, and the increased performance, two-phase drive is more commonly used than wave drive.

Half Step Drive Sequence

If four windings of a stepping motor are energized as shown in Figure 27 (so-called wave drive) the tooth alignment will be as shown in Figure 26a, and successive steps will have the normal spacing (1.8° in the case shown). Alternatively, the drive sequence shown in Figure 29 (2-phase drive) will result in tooth alignment in Figure 26b, with normal 1.8° steps. If a drive is used that alternates between wave type and 2-phase drive (Figure 31), the stepping motor output will be ½ the normal step, or .9°. All three of these drive sequences are useful. Two-phase is the most widely used "normal" drive, since it is somewhat more efficient than wave drive. Half-step drive has some interesting applications in reducing resonance problems. Compare the curves of Figure 32 where a motor was run on half-step versus full-step drive. The difficulty with half-step drive is that the two types of steps have somewhat different characteristics (particularly stiffness) due to the differing magnetic alignment.

The logic for half-step drive is shown in Figure 33 and can be used with either bipolar or unipolar drivers (page 26). For unipolar drivers, A_1, A_2, B_1 and B_2 represent individual winding drivers. In the case of bipolar drivers, a positive voltage at A_1 represents the signal that drives a positive current into the A-phase winding pair, and a positive voltage at A_2 drives a negative current into the A-phase winding pair. The same convention holds with B_1 and B_2 with respect to the B-phase winding pair.

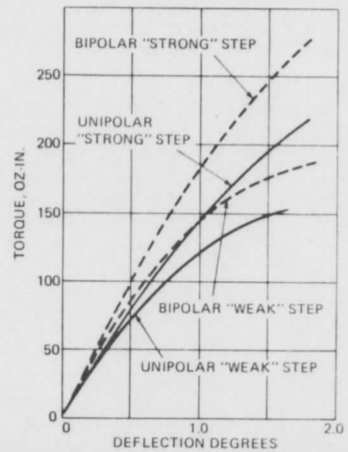


Figure 34. Comparison of Stiffness on Half-Step Drive. Test Conditions: Sigma Model 20-3424D200-F1.8 Motor. Equal Current per Step. Unipolar Current = 1.7 Amp/φ. Bipolar Current = 2.4 Amp/φ.

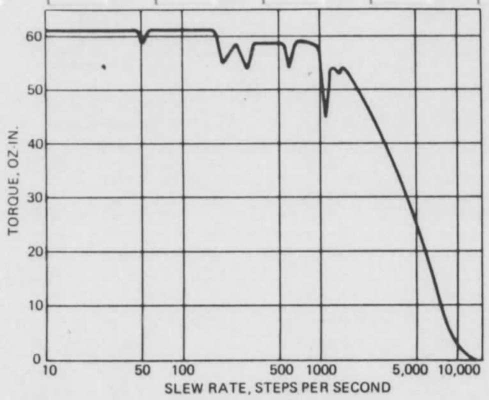


Figure 35. Motor Performance with Half-Step Drive. Test Conditions: Sigma Model 20-2223F1.4 Motor with 35V Half-Step Chopper Drive. 0.9° Step, Equal Current per Step, 2.6 Amp/ϕ

There is an important point to bear in mind when using a half-step drive system with constant current per winding. There are cases where two windings (or winding sets in bipolar) are energized, and cases when only one winding is energized. When the two windings are energized, the motor power is at a maximum and the available torque is at a maximum. When only one winding is energized, the motor power is reduced by half. This gives rise to a "strong" step and a "weak" step. Figure 34 shows the relative magnitude of the steps on a torque displacement curve. In terms of positional accuracy, if the load torque is less than 30–40% of the maximum torque, the stiffness of either step is about the same around the origin. Above this, the weak step is clearly weaker. This difference in stiffness appears as a loss of stepping torque at low frequencies, but about equal performance at high frequencies.

The difference between the "strong" step and "weak" step can be reduced by changing the current in the windings to drive the motor at rated power on every step. However, in this case, the weak step will not increase sufficiently to equal the strong step, but the difference will be reduced from 30% to about 15%.

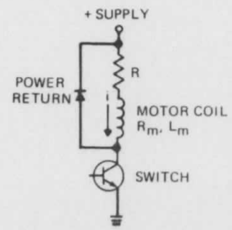
Figure 35 shows the speed-torque curves of the motor in Figure 16 with half-step logic using a bipolar drive. The reduction in resonances is worth the increased logic. If differences in stiffness is a problem, the system can be arranged to always operate on the "strong" step, or, full step operation and two pulses per step.

Power Amplifiers

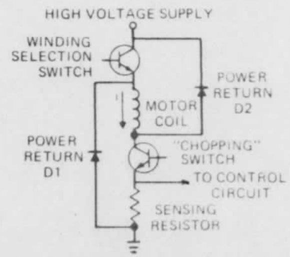
The stepping motor winding may be considered as an inductance in series with a resistance. An effective parallel resistance appears across the winding representing load power, but its effect is noticeable only with high efficiency drivers at very high speeds, and it generally has a negligible effect on driver design. The time constant of the winding, L/R, is typically of the

order of 10 milliseconds. Therefore, if a voltage source is impressed across such a winding, 95% of full current is reached in 3 time constants, or 30 milliseconds. The usual drive systems apply current to each winding at ¼ of the input pulse rate, so that each winding would receive 95% of full current at an input rate of $4/(30 \times 10^{-3}) = 133$ steps/second. In most cases, such a severe limitation on motor speed is not acceptable. For instance, a small 200 step/revolution motor which is capable of only 200 steps/second slew speed when driven with a voltage source can deliver 15,000 steps/second slew speed, when properly driven.

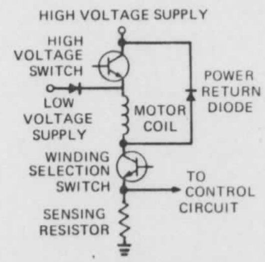
Stepping motor drive requirements vary from a few volts at perhaps 50 ma to 100 volts or more at 20 amperes. The requirements imposed upon a driver depend not only upon the particular stepping motor involved, but also upon the speed and torque requirements of the system. In general, the windings of stepping motors may be adjusted to differing impedance levels to trade voltage for current. The standard windings reflect what is believed to represent a reasonable match to available semiconductors. In any event, the current rate of rise in a winding is proportional to V/L, so that higher voltages will yield better high-speed performance up to the point where resonance phenomena (or economics!) prevent further improvement. It is not unusual for the source voltage for pulse initiation and termination to be 10, 20, or 30 times the steady state motor voltage. The principal methods for control of this "overdrive" voltage so as to limit steady state current to the correct value will be discussed in this section.



a. Resistance Current Limiting.

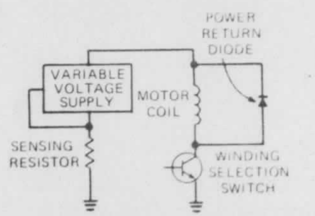


b. "Chopper" Current Limiting.



c. Bilevel Current Limiting.

U.S. Patent No. 3,560,821



d. Variable Voltage Current Limiting.

Figure 36. Means of Generating Drive Waveforms.

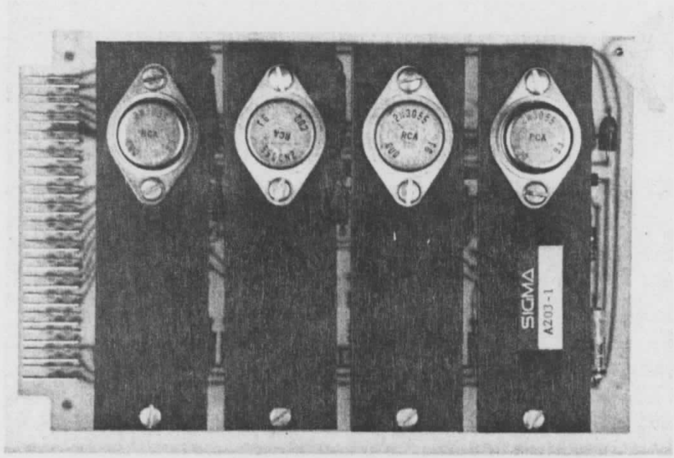
The basic objective of drive circuitry for high-speed operation of stepping motors is to provide a high voltage to move current into and out of the winding at pulse transition times, and a low voltage to sustain only the correct current during the steady-state portion of the current pulse. Generally, the required waveform is generated in four principal ways (Figure 36):

A. Series resistance is added to the winding or windings.
B. A "chopped" waveform is generated. A high voltage is applied to the windings at the beginning of the step to allow the current to build up, and then the high voltage is time modulated into pulses during the remainder of the step to hold motor current at its correct value.
C. Bi-level drive involves a high voltage source used during pulse initiation and termination, with a low voltage source during the flat top of the pulse.
D. A programmed voltage source is used (phase controlled SCR's, constant current transformers, etc.) to deliver the voltage required to maintain the current constant regardless of pulse repetition rate.

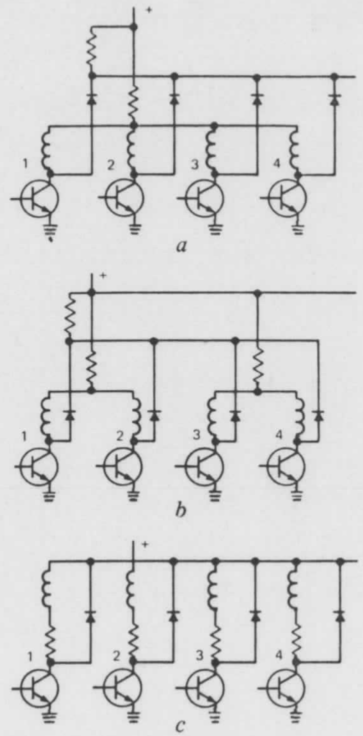
The advantages and limitations of these approaches will be examined in detail in the following sections.

Unipolar Resistance Current Limiting

The most widely used method of driving stepping motors is simply to add one or more resistors in series with the motor winding (or windings), and raise the supply voltage to yield normal motor current under steady state conditions. Some typical circuits are shown as Figure 37. For example, in the circuit of Figure 37c, the winding time constant, L/R_M is reduced to $L/R_M + R_S$ on both pulse initiation and termination as shown in Figure 38. However, the actual current rate of rise also depends upon the back *EMF* generated, and consequently speed and load (rotor dynamic response). In addition, windings A_1 and A_2 have good mutual coupling and interact in unipolar drivers. In circuits with shared resistors, the available drive voltage



Unipolar R/L Drive.



37. Unipolar Resistance Limited Drive.

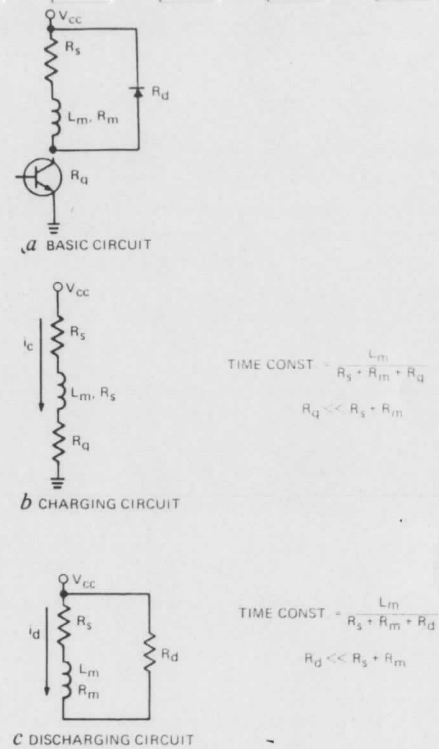
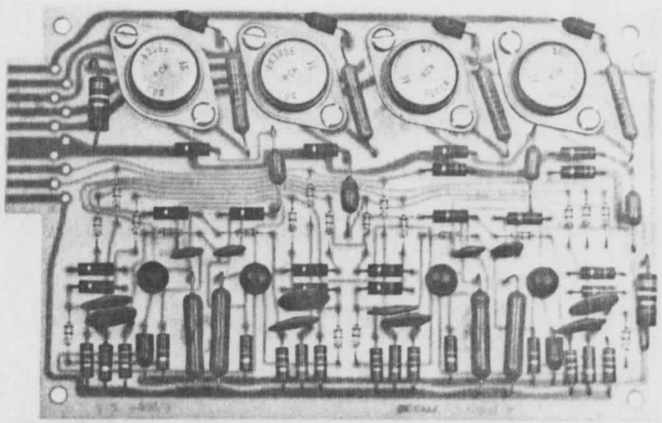


Figure 38. Unipolar Resistance Limited Drive. Charge and Discharge Circuit Time Constants.



Unipolar R/L Drive.

at pulse initiation is lower than the power supply voltage, since the other winding currents result in a voltage drop through the common resistor. Pulse termination is aided by this fact, however, since the voltage drop is in the direction to aid removal of current.

Unipolar resistance limited drives are simple and reliable, and are frequently adequate where speed and torque requirements are low. However, there are several inherent problems:

A. If voltage overdrive is raised to improve high-speed performance, the system efficiency is very low. For instance, a small (10 watt) motor may use a driver dissipating 200 watts (at 20 times overdrive).

B. The windings in the motor are not completely utilized, since the current duty cycle in the windings is 50%. Complete utilization of the windings (bipolar drive) considerably increases motor output (page 30).

C. The voltage applied to the motor windings is a decaying exponential, and the current is a rising exponential. For a given supply voltage, the current rate of rise (and the high-speed performance) is considerably less than in a system where the full supply voltage is available until the desired current is reached (see page 34).

Bipolar Drives

As previously noted, there was an improvement in performance between wave drive and two-phase drive when two of four windings were used instead of one of four. Similarly, if all four windings are energized all the time, a further theoretical increase of 41% in the ampere-turn per watt factor can be achieved. Again the full 41% increase in torque is not reached because of the non-linearity of the *B-H* curve of the iron. However, 25% to 30% improvement in torque per watt is possible.

If all 8 wires of the four windings are separate and are cross-connected as in Figure 39, currents in A_1 and A_2 will create the same sign of magnetic pole in the A phase stator poles. When the windings are driven with the bidirectional currents of Figure 34, alternate magnetic poles are created in the stator as in a unipolar drive, except that the two-phase windings aid each other. The logic required is the same as the unipolar two-phase logic

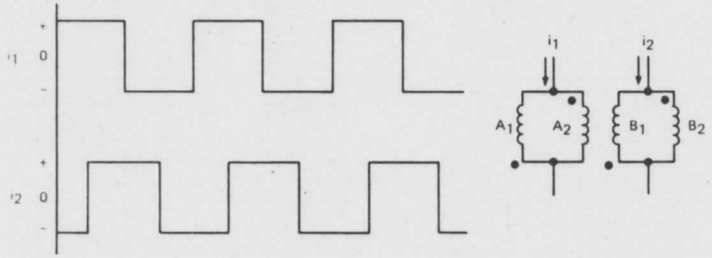


Figure 39. Bipolar Two-Phase Drive.

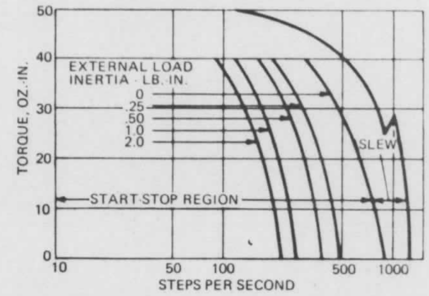


Figure 40. Motor Performance Using a Bipolar Driver. Test Conditions: Sigma Model 20-2223D200-F6 Motor with 15 V Bipolar R/L Driver. $R_S = 8.5\Omega$, $I_\phi = 1.25$ *Amp,* $P_m = 9$ *Watts, Driver Power = 38 Watts.*

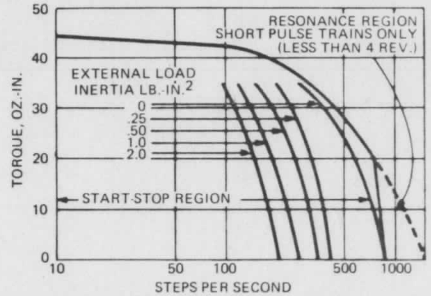
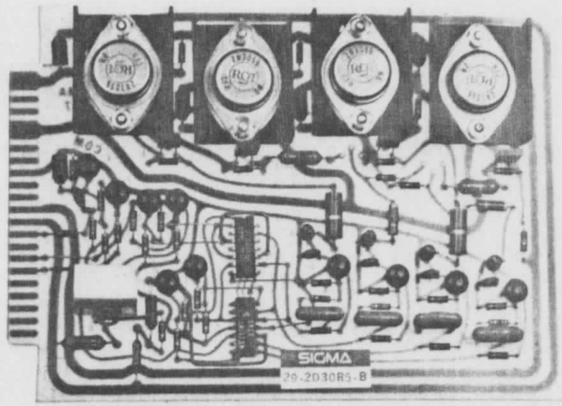


Figure 41. Motor Performance Using a Unipolar Driver. Test Conditions: Sigma Model 20-2223D200-F6 Motor with 28V Unipolar R/L Driver. $R_S = 24\Omega$, $I_\phi = 0.9$ *Amp.,* $P_m = 10$ *Watts, Driver Power = 51 Watts.*



Bipolar R/L Drive.

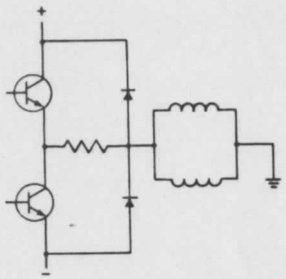


Figure 42. Bipolar Resistance Limited Driver

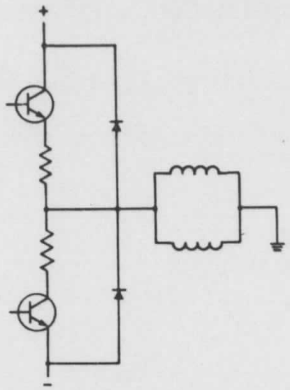


Figure 43. Bipolar Resistance Limited Driver-Split Resistor.

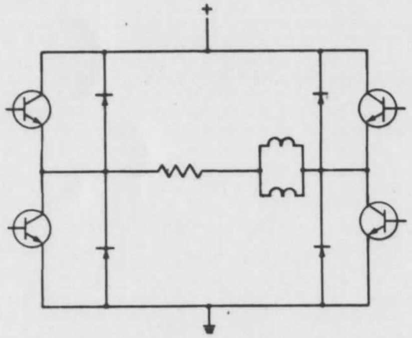


Figure 44. Bipolar Resistance Limited Driver-Full Bridge.

shown in Figure 30. The improved motor efficiency due to bipolar operation may be realized as increased toque and speed for a given motor wattage (20%–40% as compared to unipolar R/L drive), or as a 50% reduction in motor power while maintaining torque and speed characteristics equal to that of the unipolar case. Figures 40 and 41 show the comparison of a 15 volt bipolar driver and a 28 volt unipolar driver using a 20–2223D200–F6 with 9 watts of motor power.

One practical method of obtaining the required drive waveforms is the split supply system shown in Figure 42. Here equal value positive and negative supplies are required, but the total number of switches and the overall complexity of the system are approximately the same as for a simple unipolar driver. Because the power switches are essentially in series across the supply voltage, it is necessary to incorporate delay circuitry to prevent

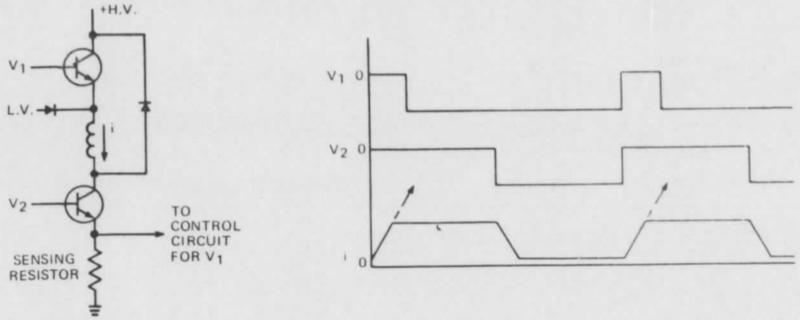


Figure 45. Bilevel Drive.

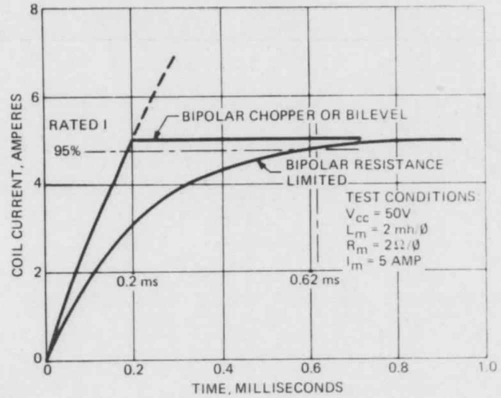


Figure 46. Comparison of Current Rise Times.

one switch from being turned on while another one is conducting. Alternatively the power resistors may be split, as shown in Figure 43, so that any slight overlap of switch conduction will not be harmful.

Another version of bipolar drive uses full bridge operation, as shown in Figure 44, requiring only a single supply voltage. This convenience is obtained at the expense of doubling the required number of power switches to 8 per motor. In this system, the same switch timing considerations apply as in the split supply case, and the use of delay networks can be avoided in the same way, by using extra power resistors. It should be noted that because of the operation of the bridge, the total peak-to-peak voltage applied to the motor windings is twice the supply voltage. For this reason, the full bridge output transistors can drive a winding at twice the voltage (for a given transistor collector rating) of the split-supply bipolar configuration or the unipolar configuration.

Bi-Level Drive

One system for obtaining a high current rate of rise efficiently involves the use of two supplies – a high voltage supply for pulse initiation and termination, and a low voltage unit to supply sustaining current during the pulse flat top. One approach to this type of circuit is shown as Figure 45. The high voltage supply is turned on until the motor current reaches the operating level, when the high voltage switch is turned off. At the end of the pulse, the lower switch is turned off, and the current in the winding is returned to the high voltage supply as indicated in Figure 45. This action results in rapid pulse initiation and termination, with no inherent switching losses. Further, the current rate of rise is much higher than in the resistance-limited case, where the voltage is a falling exponential. This is illustrated in Figure 46, where the two cases are compared for equal supply voltage.

Current Fed Drive Circuitry

Regardless of the basic drive system (unipolar or bipolar) high driver efficiency is attainable if the voltage source can be programmed to deliver the required current at all stepping rates. A convenient method of programming voltage efficiently is in the initial conversion from the power line, using such methods as ferro-resonant transformers, saturable reactors, and SCR phase control. All of these methods are inherently slow in response ($\approx$ 50–200 milliseconds), since they are limited by the necessity of filtering line frequency (a three-phase system is considerably faster than the conventional single-phase approach because of the inherent reduction in carrier lag). This discussion will focus on the SCR phase control method, but it is generally applicable to the other schemes.

A basic block diagram of an SCR phase control system is shown as Figure 47. Also, response times to a current step are indicated. This type of motor drive system has the following advantages and limitations:

1. This mode of operation is highly favorable with regard to resonance control. Since only enough voltage is applied to force rated current through the stepping motor windings, the problem of rotor overshoot and resonant modes (page 5) is greatly reduced. Motor operation is smooth, and it is not necessary to avoid or rapidly traverse critical resonance regions. Another result of this mode of operation is that the low frequency torque enhancement described on page 8 does not occur, since high overdrive does not exist at low speeds. In the block diagram of Figure 47, it is important to note that the average current to the drive system is the factor that is regulated. Because of this, as the frequency of operation is increased, the average voltage is likewise increased to continue forcing the set level of current through the motor winding, until the voltage limit of the supply is reached. At high speeds, an appreciable fraction of the motor current is returned to the supply by the recirculating diodes, but this factor is effectively ignored by the regulating system which continues to adjust the voltage to the system on the basis of average drain from the supply. The result of this type of operation is that the high speed torque is enhanced, but the RMS current through the windings, the winding RMS voltage, and consequent motor dissipation, are increased during high-speed operation. This type of operation results in the greatest power output from a given stepper, but thermal factors,

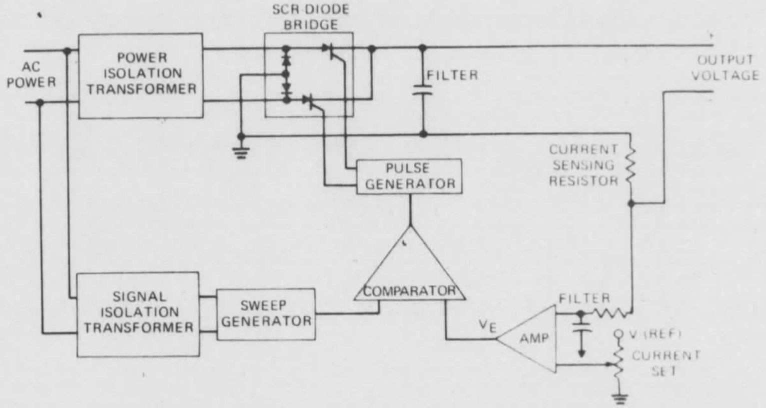


Figure 47. Block Diagram of SCR Controlled Constant Current Source.

including duty cycles, motor construction, heat sinking, and ambient temperatures, must be considered carefully in the design of a system of this type (page 39).

2. Relatively long response times limit the start-stop performance. When the system is at rest, a low percentage of the supply voltage is applied to the driver. For instance, in a system that will deliver 100 volts at high speeds, the voltage may be 3 volts when the motor is stopped. Since the voltage can rise only at a relatively slow rate, start-stop operation is severely limited. However, this limitation may not present much difficulty in a ramped system, where the motor is accelerated to a high speed after starting at a low speed. In this case, the time to accelerate to high speed is impaired little by the driving system, since the response of motor and load inherently limits acceleration.
3. Care must be exercised in system design to prevent excessive current flow in the switching system. This may occur if the system is suddenly switched to a low speed after a period of high-speed operation. In this case, the system voltage is high to allow high-speed running, and the filter capacitor is fully charged. If the motor is suddenly switched to low-speed operation, the full capacitor charge will be dumped through the switches, with possible excessive current flow or switch dissipation. In normal ramped operation, of course, the motor speed is decelerated gradually and this problem does not arise.

Chopper Drive Circuitry

Another high-efficiency system that offers certain advantages in stepping motor driving is the so-called "chopper" system for current limiting by means of voltage modulation. With this arrangement, the full high voltage supply (10 to 20 times motor voltage) is applied to the motor winding until the correct current level is reached (Figures 48 and 49). The voltage

is then switched off, and the current is allowed to circulate in the motor winding. When the current decays to a predetermined level, voltage is again applied to drive the current back to the correct level. This cycle is continued throughout the driving pulse time. At the termination of the driving pulse, the motor winding current is recirculated rapidly to the high voltage supply. Essentially, the operation involves a high voltage to initially charge the motor winding, indicating a low average voltage (achieved by time modulation) to sustain the current, and high voltage return to discharge the motor winding inductance. In this case, the effective motor voltage is increased at high stepping frequencies, since the voltage is switched on to the motor for a high percentage of the time. The current sensing system used, as in the current-fed system, does not take account of the current circulating in the motor winding. Therefore, when high stepping frequencies are used, the RMS voltage, current, and motor power increase as discussed on page 39.

Chopper operation is inherently well suited to start-stop applications – high voltage is available to accelerate the rotor as rapidly as possible, with a

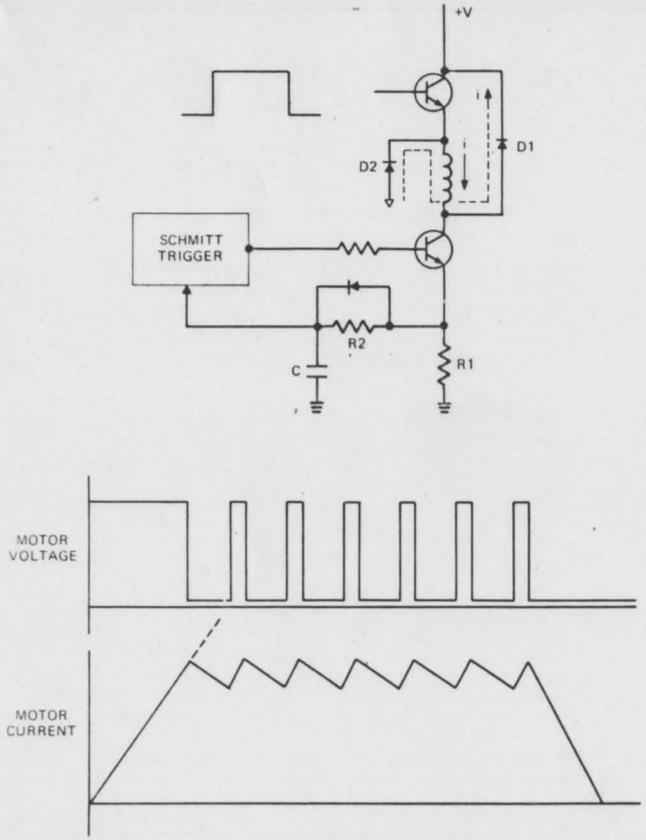


Figure 48. Unipolar Chopper Regulator Utilizing Motor Inductance.

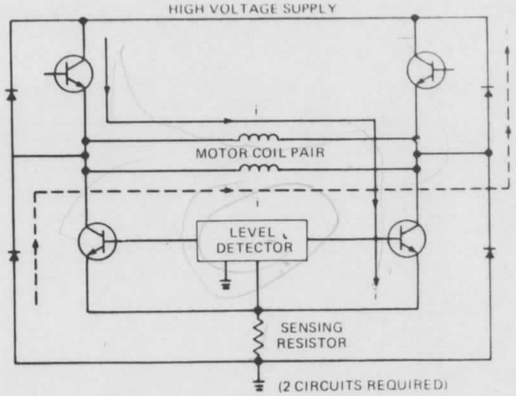
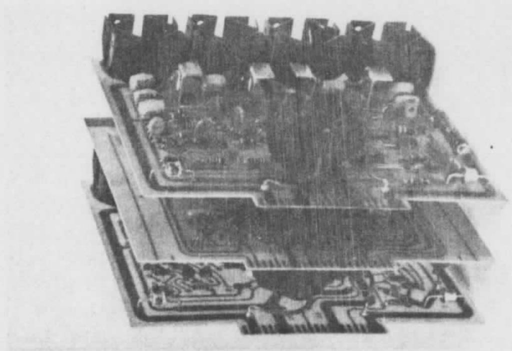


Figure 49. Bipolar Chopper Phase Driver.

maximum of low frequency torque. For ramped applications, resonance phenomena must be considered, and resonant regions avoided. It is generally possible to accelerate through resonance regions, but it may not be possible to achieve stable steady state operation in such regions, particularly the major resonance at about 1 KHz in Sigma Series 20 motors. The use of half-step driving is one method by which resonance characteristics may be overcome.

Performance Comparison

Measured results using one particular motor (Sigma Series 20–4270) and high voltage supply (65V) are shown as Figure 50. With the chopper drive the low frequency torque is high and start-stop characteristics are good, but note the resonant regions. A bi-level drive would give approximately the same results. The current-fed driver is smoother in operation, but has



Bipolar/Chopper, 65V.

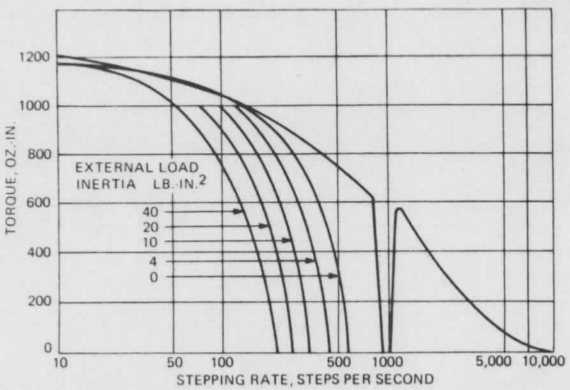


Figure 50. Motor Performance Using a Bipolar Chopper Drive. Test Conditions: Sigma Model 20-4266TD200-F0.6 Motor with a 65V Bipolar Chopper Drive. I_ϕ = 7.5 Amp, P_m = 34 Watts, 1.8° per Step.

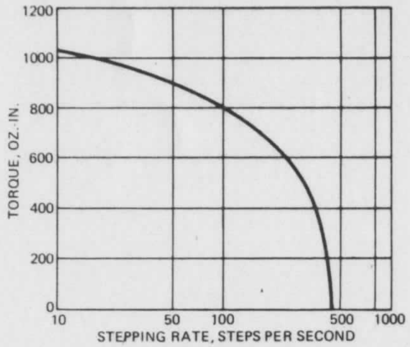


Figure 51. Motor Performance Using a Unipolar Resistance Limited Drive. Test Conditions: Sigma Model 20-4266TD200-F6 Motor with Unipolar R/L Driver. I_ϕ = 5.3 Amp, P_m = 34 Watts, V_{CC} = 65 VDC.

poorer start-stop characteristics and low frequency torque. All three types of high efficiency drive would give the same results at high stepping rates (1.5KHz). This is true because they present identical waveforms to the motor in this region, where they all become voltage sources switched by a transistor bridge. The difference between the drives is only in the method used to limit motor current at low stepping rates. For comparison purposes, Figure 51 is the curve of the same motor and power supply with a conventional unipolar resistance-limited driver included – the difference in power output and system efficiency is rather striking.

Figure 52 shows the same curves as Figure 50 except that the motor is

taking half steps (0.9° per step). Note the improvement in performance at the resonant region.

Motor Heating Considerations

As discussed previously, high efficiency drives result in an increase in RMS motor current and voltage. Although an appreciable fraction of the power increase may be delivered as output power in a loaded motor, there is still a considerable increase in motor dissipation at high speeds under high overdrive conditions. It is well to note that an increase in motor dissipation also occurs in inefficient drives, such as resistance-limited systems. The dissipation is basically the result of the high overdrive required for high speeds, however it is applied.

The key to high-speed motor performance has been to use higher and higher voltages to approximate a current source in order to drive the current into the highly inductive motor winding. A number of schemes are used to limit the low frequency current, ranging from series resistors to ramped voltages or switching current regulators ("choppers"). Regardless of how the current is controlled, at high frequencies the voltage across the windings approaches the supply voltage, causing increased switching losses in the rotor and stator, which can exceed the normal power rating of the motor.

The power rating of a motor is limited by the maximum allowable temperature of the insulation system used in the motor. In accordance with NEMA specifications, a motor with Class B insulation has a maximum winding temperature rating of 130° C. Therefore, the allowable temperature rise of a Class B motor cannot exceed 130° C minus an allowance for "hot spots," and minus the maximum expected ambient. Accordingly, the motor power rating is equal to that total input power which produces a winding temperature rise compatible with the insulation system used. In general, the ratings for most stepping motors are based on an unmounted, stopped, or slowly running motor for an expected 55° C or 60° C maximum ambient.

If the current or voltage ratings (derived from the power rating) are used at

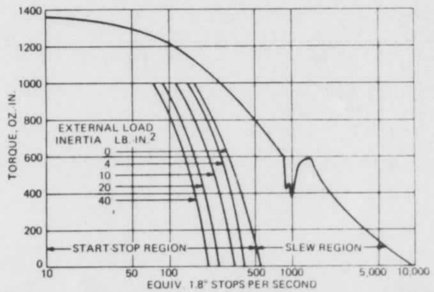


Figure 52. Motor Performance with Half-Step Drive. Test Conditions: Sigma Model 20-4266TD200-F06 Motor with 65V Bipolar Chopper Half-Step Drive. 7.5 Amp/φ, 0.9° per Step.

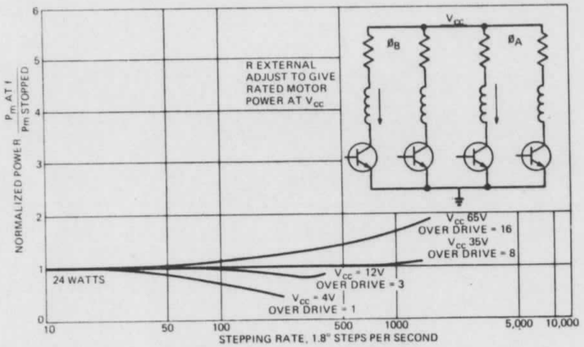


Figure 53. Effect of Overdrive on Input Power to a Motor. Test Conditions: Sigma Model 20-3437D200-F0.75 Motor with Unipolar R/L, Two Phase Drive. No Motor Load.

low frequencies and low ratios of power supply voltage to motor voltage, referred to as overdrive, the motor temperature rise will be safe. However, if very large overdrive ratios are used, the input power to the motor can rise above rated power.

Unipolar, Resistance Current Limiting

Figure 53 shows the normalized motor power for an unloaded motor as a function of frequency and power supply voltage for the common R/L method of driving stepping motors (page 28). The motor is excited by applying rated current to the motor in the stopped condition, with the circuit as shown in Figure 53. The motor used was a Sigma Model 20-3437D200-F0.75, rated at 24 watts.

From Figure 53, the power input to the motor is always equal to or less than the DC power input for overdrive ratios up to 8. For ratios over 8, the motor power increases with frequency: Specifically, for a ratio of 16, the power at 1500 sps is 1.8 times the low frequency value. Consequently, motor overheating could be a problem if the motor had to run continuously at this frequency. The reason for this power increase is as follows: Although the current is decreasing with frequency, and hence the I^2R heating is dropping, the stator and rotor switching losses are increasing with frequency. These represent power dissipated in the motor. Furthermore, the RMS voltage across the winding increases with frequency, adding a further increase in core losses. The switching losses increase with increasing overdrive because the voltage across the motor windings eventually reaches V_{cc} at high speeds.

Bipolar Resistance Current Limiting

Another method of driving motors for higher performance with resistor current limiting consists of driving all the windings with bidirectional currents, or two-phase bipolar driving (page 30). Figure 54 shows the

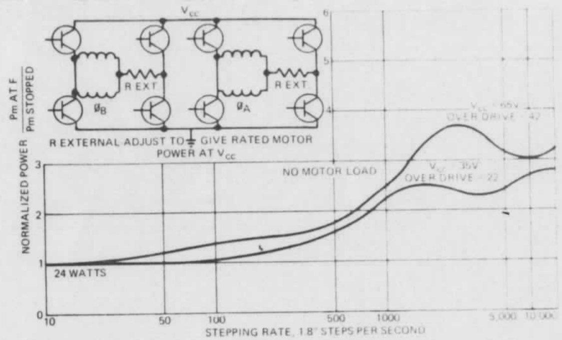


Figure 54. Overdrive Characteristics of Motor Using a Bipolar Drive. Test Conditions: Sigma Model 20-3437D200-F0.75 Motor with Bipolar R/L, Two-Phase Drive. No Motor Load.

normalized motor power with bipolar R/L driver. The motor is the same as used in Figure 53. In the examples cited, the motor power increases dramatically with frequency. The maxima are created when the I^2R losses are still large while the core losses are increasing. Eventually, the I^2R losses decrease faster than the switching losses. At very high frequencies, the losses are almost all core loss. At frequencies above 10K sps, the motor power continues to rise.

It should be noted that bipolar switching doubles the effect of the power supply voltage because the peak-to-peak swing across a motor winding is twice the supply voltage. In addition, the rated motor voltage is less when two windings are connected in parallel because the resistance level is

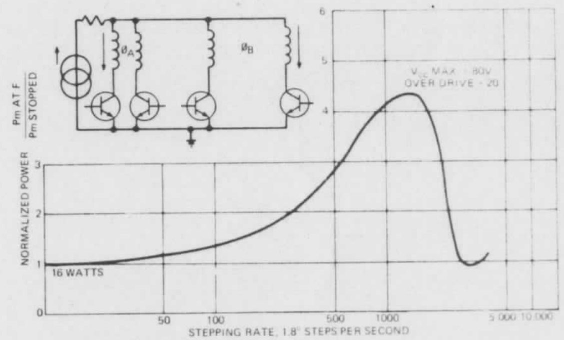


Figure 55. Overdrive Characteristics of Motor Using a Constant Current Drive. Test Conditions: Sigma Model 20-3437D200-F0.75 Motor with Constant Current Unipolar, Two-Phase Drive. No Motor Load.

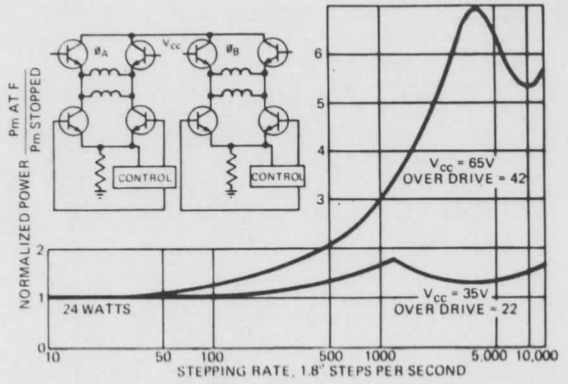


Figure 56. Overdrive Characteristics of Motor Using a Bipolar Chopper Drive. Test Conditions: Sigma Model 20-3437D200-F0.75 Motor with Bipolar, Switching, Current Regulator, Two-Phase Drive. No Motor Load.

halved, but the current in the pair only increases by $\sqrt{2}$. Thus the effective overdrive ratio is increased for the same supply voltage.

Unipolar Constant Current

Similar increases in motor power occur with "constant current" drives (page 34). Figure 55 is the power-frequency plot of a ferro-resonant constant current source, which adjusts the supply voltage upward as the motor current tends to decrease with speed. With this driver, the available output voltage varies from 12 volts to 80 volts. The driver is basically a unipolar driver as in Figure 53. The motor is the same as in Figure 53. As indicated, the motor dissipation rises to more than 400% of the rated motor power (page 35).

Bipolar Chopper

Another constant current driver uses a switching regulator to control the motor current. Essentially, a winding is connected by a 4– transistor bridge to a voltage supply and the winding current is sensed in the common side of the bridge. The bridge is turned on until the current reaches rated value and then turned off. During the off interval, the winding current is recirculated to the power supply through diodes. The basic driver is as shown in Figure 49. The power-frequency relationship is shown in Figure 56. The curve for the 65 volt circuit is shown for reference purposes only. It is not recommended for use with the small motor used in the previous examples. It does illustrate the effect of very high voltage overdrive conditions.

For purposes of comparison, a much larger motor was run on the 65 volt bipolar switching regulator. This combination will deliver a peak output power of about ¼HP at 2000 sps. The motor is rated at 34 watts and is a Sigma Model 20–4666D200–F0.6. Figure 57 is a power-frequency plot of this motor and driver, with the motor unloaded. The increase in power input is again dramatic.

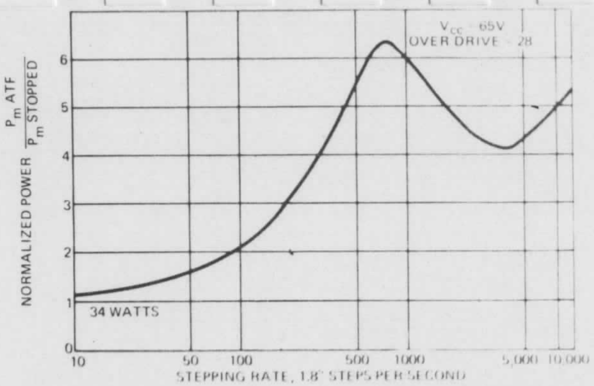


Figure 57. Overdrive Characteristics of Large Motors Using a Bipolar Chopper Drive. Test Conditions: Sigma Model 20-4266D200-F0.6 Motor with Bipolar, Switching, Current Regulator, Two-Phase Drive. No Motor Load.

The increase in stepping motor performance has been achieved at a hidden cost – heat in the motor. The motor ratings must be used with an eye to the type of driver used. When high-performance drivers are used, the duty cycle of the application must be considered. A driver capable of running a motor at 10,000 sps with useful torque may have regions where the input power at lower frequencies is many times the power rating of the motor.

All these tests were made on an unloaded motor in order to show the trends more clearly. In general, a loaded motor will have slightly lower losses. In the case of resistance limiting, the through-put power tends to reduce the motor voltage at particular frequency, reducing switching losses. Furthermore, the rotor develops a lag angle which tends to reduce losses. However, the decrease in motor losses caused by loading rarely amounts to more than 20% of the unloaded losses.

Summary of Drive Circuits

The simplest and least expensive drive circuit is usually the resistance-limited unipolar circuit. However, it fails by a wide margin to yield the maximum output available from a given stepping motor, and is inefficient from the standpoint of power requirements and system heating.

The bipolar resistance limited system requiring only a modest increase in complexity, considerably improves the results of the unipolar circuit. The available improvement can be taken as improved torque (20%–40%) and speed (30%–50%) or reduced system power (50% reduction from unipolar case).

The high efficiency systems (bi-level, current-fed, chopper) allow dramatically improved motor performance and system efficiency, at the expense of complexity and cost. Obviously, the designer must weigh his performance requirements carefully before deciding upon a particular motor -driver combination.

APPLICATION CONSIDERATIONS IN STEPPING MOTOR SYSTEMS

Stepping Mode

Occasionally, stepping motor systems applications are simple and straightforward. Perhaps the load is very light and well controlled, the speed requirements are low, and the environment constant and agreeable. In such a case, probably the only concern would be the lowest priced motor and driver available that would fit in the space allocated. Or, a heavy machine tool load is to be driven as fast as possible, because reduced cycle time is extremely valuable. Here, the largest motor and best driver available might be well justified.

Unfortunately, most applications tend to lie between these extremes, and the designer must make a choice of systems based on a careful comparative study. First and foremost, the load requirements must be studied thoroughly – not only to determine the load parameters as well as possible, but also, if possible, to consider modifications to the load to optimize the system for stepping motor drive. For instance, in general, stepping motor systems are more sensitive to inertial loads than to friction loads. Therefore, if fast response and quick settling are desired, the most favorable load configuration will probably be the one that minimizes inertia at the stepping motor, and effort spent in this direction is likely to be most rewarding. The friction load is the other basic load parameter. Friction and inertia, combined with the required load speed and acceleration, determine the basic requirements on the stepping motor system, since friction determines the power output, and inertia and speed define the amount of kinetic energy that must be put into the system upon starting and removed upon stopping. Although it is not practical to cover all load configurations likely to be encountered, inertial characteristics of some common applications and conversion tables for numerical values are given in the appendix.

In some cases, required speed and resolution determine the step angle in a stepping motor system, but in others a choice is available, since an effective gear ratio may be obtained through a timing belt, lead screw, linkage, or other means. In these cases, it may be useful to compare motors of differing step angles. Usually, the simplest approach is to consider shaft speed in RPM, or some other convenient measure. For instance, a 200 step/rev (1.8° step) device at 200 steps/sec is moving at 1 RPS, or 60 RPM. A 24 step/rev (15°/step) motor achieves this output speed at 24 steps/sec.

In making comparisons involving stepping motor systems with differing step angles and speed-torque characteristics, it is useful to plot speed in RPM against torque and power output. Power output in watts can be calculated from the formula P_{watts} = Speed (steps/sec) × Torque (in.-oz.) × .0444 ÷ steps per rev. For various step angles, the formulas are:

$$P_{watts} = 2.22 \times 10^{-4} \times \text{Torque (in-oz)} \times \text{Speed (steps/sec) for } 1.8^\circ \text{ step angles}$$

$$P_{watts} = 1.84 \times 10^{-3} \times \text{Torque (in-oz)} \times \text{Speed (steps/sec) for } 15^\circ \text{ step angles}$$

Power output curves on stepping motors reveal a broad maximum (Figure

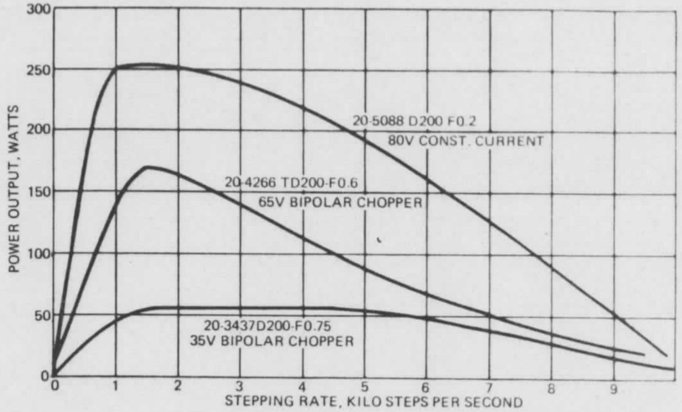


Figure 58. Power Output Curves.

58) which arises from the nature of the power output relationship – at very high speeds, zero torque (and zero power) is delivered; at zero speed, torque is high but power delivered is necessarily zero. If other system factors allow, consideration should be given to operating at the peak of the power output curve in order to obtain maximum performance from the motor-driver combination.

Operating point selection and motor driver choice must take into account thermal conditions in the motor. As discussed on page 39, high performance drivers frequently lead to increased motor dissipation at high speeds. Since motor thermal lag is generally fairly long (thermal time constant of 20 minutes or more), it is frequently possible to allow high motor dissipation for short periods of time if the net effect is not one of excessive motor temperature rise. This is basically a classic duty cycle problem – the criterion is final temperature rise, considering the effects of ambient temperature, motor heat-sinking, and operating times. It should be emphasized that the limitation on power output of most stepping motors is simply temperature rise – more torque is available at higher than rated currents if the final temperature can be held to its rated value.

The best way to determine if a motor will overheat is to measure the temperature rise of the motor winding by measuring winding resistance after it has operated at the worst duty cycle for a period of 3 or 4 hours. This long period is required because the thermal time constant of most motors is in excess of 20 minutes. If the winding resistance is measured when the motor is at room temperature and again at the end of a period of operation at the worst duty cycle, the temperature rise of the winding is approximately 2.5 times the percentage resistance increase from the room temperature resistance. This temperature rise should be limited to a safe value recommended for the motor based on the maximum ambient expected. Heat radiators or fan cooling are sometimes required.

In general, most control systems have only limited periods where high speeds are required. In these, heating is not a severe problem. Great num-

bers of successful applications have been made that combine high-performance drivers and stepping motors to achieve fast, precise positioning with excellent reliability.

In making a choice of driver-motor combinations, resistance-limited drivers frequently offer adequate performance when used in conjunction with a suitable motor. However, serious consideration must be given to the power dissipated in the limiting resistors, and the effects of the resultant temperature rise on the remaining system components. In modern systems, it is quite probable that limiting resistor dissipation will represent a significant percentage of total system power. Considerations of this kind not infrequently lead the designer to consider a more efficient driving system, even though the actual system drive requirements could be met adequately by the simpler but less efficient resistance-limited drive.

Another category of trade-off arises when the stepping motor system is used as a high-speed positioning device, and angular accuracy is critical. Here, both start-stop speed and damping characteristics must be considered. Unfortunately, drives that yield high start-stop rates tend to be poor in settling characteristics. Reverse pulse damping on the last pulse of a train (page 15) and/or current-fed drive (page 34) may be satisfactory answers for damping problems. Mechanical dampers are sometimes used, but their life span may be inadequate for high reliability systems.

Mechanical design for stepping motor systems must take into account fits, mounting dimensions, etc., but it is often sensible to plan the design for a possible future change in motor size. It often happens that it is desirable to improve the performance in speed or torque of a system after the preproduction or production stage is reached. This can occur because the actual load was not as estimated, or it may be that the product will be more marketable if its capability can be increased. In any event, the design of a stepping motor family typically will include a number of different length motors with given frame diameter. This is done not only for economic reasons (much of the tooling on a motor is related to diameter, not length), but also to maintain a favorable torque/inertia ratio. Torque increases directly with the stack length of a motor, as does rotor inertia. However, as a first order approximation, torque increases directly as diameter, but the inertia goes as the square of the diameter. Therefore, to obtain high performance motors, it is preferable to make a long motor (related to diameter) rather than a short, fat motor. Obviously, this approach reaches a limit when it becomes impractical to hold tight tolerances on air gap as the rotor and stator lengths are increased. However, the point is that it is frequently possible to upgrade system performance rather simply by increasing motor length – if provision has been made for such a change. Another important mechanical consideration is system backlash or "tightness." Stepping motors are inherently a transient device, and system oscillations, with consequent poor performance,, are readily excited by the pulsing torque delivered by a stepping motor. The ideal mechanical system for stepping motor drive has good fits and low backlash characteristics, and, preferably, the lowest possible inertia.

Coupling of stepping motors to the load is frequently treated rather casually – but it can be the source of considerable problems. The ideal

coupling is somewhat compliant, but not sloppy or subject to deterioration with time and operation. Attachment of couplings to stepping motors with set screws is satisfactory only for the smaller sizes. Larger motors should be pinned or keyed – the discontinuous stepping torque will soon loosen less positive fasteners over even short periods of time.

In the broad sense, probably the most practical way to apply stepping motor systems is with a healthy dose of conservatism, particularly as regards load conditions. Many loads change appreciably during system life, inevitably, it seems, for the worse. Further, it is desirable many times to handle transient load conditions that occur only infrequently. Adequate performance margins are the realistic approach to such problems.

Other Modes of Application for Stepping Motors

Stepping Motors are frequently used in modes other than straightforward digital load positioning. Although basic motor operation is the same in all modes, it may be useful to consider these modes of operation separately.

Servo Motor

In many applications, open loop stepping motor systems are competitive with closed loop servos. However, stepping motors are sometimes used as the mover in servo systems (Figure 59). In this application, the stepping motor is generally in the digital, or stepping, mode. Therefore, the system is limited in resolution to the value represented by one step. In essence, this amounts to a bang-bang servo where an error signal results in a quantized response, and the dead band necessary for stability is represented by the distance between steps. This type of system has resolution limited by the step size (as seen at the load through any appropriate gearing) but it does have some interesting features. Holding torque is always applied to the load; almost full torque can be generated by the motor with a shaft position error of less than the dead-band, i.e., no system error signal. Speed of response is also independent of the load characteristics: the load is driven to the system null at the same speed regardless of the magnitude of the error. Overshoot problems are easily minimized: in effect, the stepping motor system controls overshoot on every step. The stepping motor does

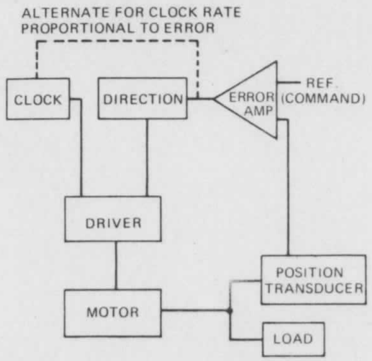


Figure 59. Use of Stepping Motor as Servomotor.

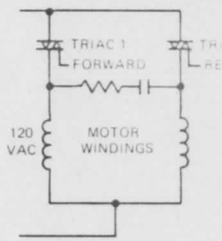


Figure 60. Synchronous Servo.

not have the brush problems of DC servos, and is suited for operation over a wide range of frequencies compared to conventional 2-phase AC servo-motors.

Synchronous Servo

A method of using a stepping motor in an inexpensive servo system is shown as Figure 60. The synchronous mode of operation (page 50) requires a minimum of extra hardware to provide a reversible drive. This operating mode utilizes the low synchronous speed of the stepping motor when operated directly from line frequency (72 RPM for a 200 step/rev motor operated at 60 Hz). In this type of operation, low speed and relatively high torque are available without a gear box. The motor is well damped for positive start-stop characteristics, and can be stalled indefinitely without incurring damage.

Speed Control

The stepping motor with appropriate driver offers the possibility of virtually infinite speed control range, since the low speed limit can be as low as desired. Obviously, the output is stepped and not smooth, but in many applications this is not objectionable. Further, the output speed is unaffected by load up to the torque limit of the motor, and the speed can be programmed or controlled from an external source in either analog or digital fashion.

This variable speed capability allows two independent motors to run at identical speeds in remote locations or permits two motors to run at precise ratios of each other, independent of load. Figure 61 is the block diagram of a variable ratio system.

Encoder Operation

Shaft position encoders have been used in conjunction with stepping motors for two principal reasons:

1. **Acceleration Improvement**

   If the shaft position can be determined accurately as a function of time it is possible to control drive pulse timing to obtain maximum acceleration. Since the dynamic shaft position depends upon load, a coupled shaft encoder takes into account load characteristics to allow maximum possible acceleration. The encoder chosen must be of such design as to allow determination of direction (usually

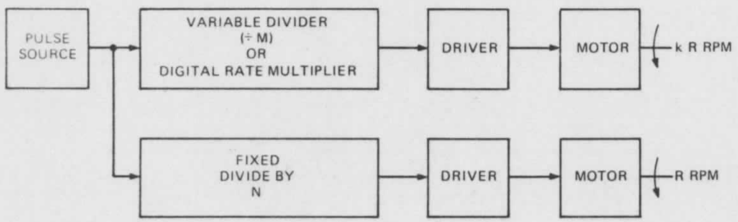


Figure 61. Variable Ratio Motor Drive System.

accomplished with quadrature tracks), since overshoots of shaft position otherwise could be interpreted incorrectly as a forward pulse by the decoding circuitry. A considerable amount of sophisticated logic is required to use an encoder, but it does offer improvement of acceleration that is difficult to obtain in any other way.

2. **Step Confirmation**

   An encoder, again with two quadrature tracks to decode direction information, can be used to ensure that all command steps have been taken by the motor. This system basically guards against transient load conditions, or momentary malfunctions in the motor driver or logic system.

SYNCHRONOUS OPERATION

An important type of operation for stepping motors is the line-operated synchronous mode. The required driving waveform consists of two sine waves, 90° out of phase. Thus, synchronous operation is closely parallel to bipolar drive at a fixed frequency. In effect, the motor takes a "step" when either of the input sinusoids assumes either a positive or a negative maximum – therefore, the "stepping rate" corresponds to 4 times the line frequency.

For instance, with an input line frequency of 60 Hz, a motor will take 240 steps/sec. With a 200 step/rev motor, this corresponds to 240/200 rev/sec, or 72 RPM.

The required 90° waveform is conveniently generated with an RC network, adjusted to yield nominal 90° phase and output voltage of the same magnitude as the line. (Although this is the conventional method, other means should not be overlooked. For instance, if 3-phase power is available, a Scott T may be a useful solution, particularly if large numbers of motors or high power motors are to be driven.)

The components in the RC phase shifting network have considerable effect on motor performance, and it is possible to optimize various parameters by varying these components somewhat from their nominal value's (See Figure 62). For instance, audible noise can be sharply reduced, at the expense of some torque, by correct choice of component values. Also, starting characteristics under inertial load are affected considerably by variation in component values. However, in experimenting with such changes, it must be realized that under some conditions, starting characteristics can be affected adversely, even to the point that occasional weak reverse starting may occur.

As with digitally operated stepping motors, synchronous motors have differing starting and running characteristics, particularly in the presence of inertial loads. Curves should be consulted to determine if a proposed operating mode is within the capabilities of a given motor. Figure 63 shows the typical performance of a Sigma synchronous motor when used with the recommended "best average" phase shift network shown.

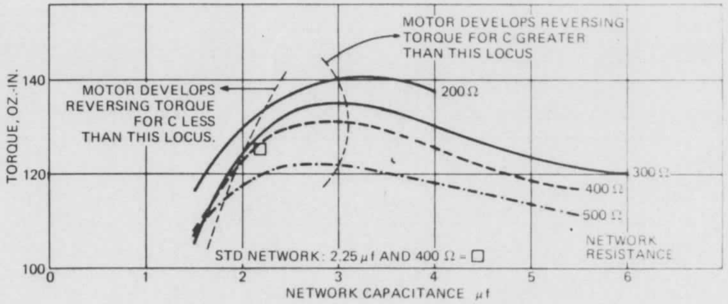


Figure 62. Running Torque vs. Network Parameters. Test Conditions: Sigma Model 20-2235S72-A120, Load Inertia - 0.8 lb.-in.^{2}, 120V–AC.

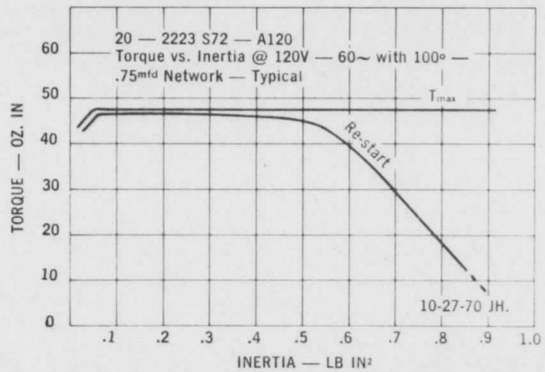


Figure 63. Performance with Standard Phase Shift Network.

APPLICATIONS OF STEPPING MOTOR SYSTEMS

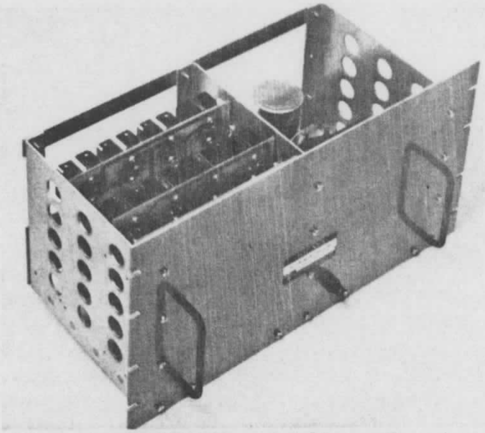
In this section, a brief description will be given of actual applications of stepping motor systems and the criteria used in the selection of the optimum solutions.

High Power, High Speed Drive for Milling Machines
Point-to-point numerical control systems for machine tools typically emphasize high power at high speeds, along with high resolution. A 5-pitch lead screw will yield a resolution of .001″ when driven with a 200 step/rev. motor; a 10-pitch screw will give a .0005″ resolution. To achieve 120 in/min with a 5-pitch screw requires a stepping rate of 2000 steps/sec. Attainment of this speed dictates a ramped system for acceleration and deceleration of the stepping rate. Typical ramp times for this application are of the order of .1–.3 seconds. As is obvious from the curves of motor performance (this application generally requires a Sigma 20–4270 or 20–4288 class of motor), the available speed depends greatly upon the frictional load encountered. At this point, the system designer faces a trade-off situation.

Friction levels can be reduced appreciably by using ball screws in the driven machine – but the machine cost is increased appreciably. A high drive circuit voltage will increase high speed torque (high speed torque is roughly proportional to drive voltage in this case), but heating factors (page 39) and resonance characteristics must be considered. When all of of these factors are taken into account, the best solution frequently involves a heat-finned motor and a constant-current type of drive with high output voltage (50–100 volts). This system is smooth in performance (minimal resonance problems) and capable of reaching high speeds. This type of drive, although not capable of high start-stop speeds, can accelerate excellently to high speeds so that machine cycle time is good.

For contouring systems, the system requirements change appreciably. Contouring is usually done at stepping rates from 0–500 steps/second, and the system is required to start and stop in this range. High slewing speed requirements (rapid traverse) are also imposed on the stepping motor system. To meet these requirements, a drive such as the bipolar chopper is frequently used in conjunction with the Sigma Model 20-4270 or 20-4288 motor. The high start-stop speed and slewing requirements are met by this drive, but at the expense of exposure to resonance phenomena. The major resonance at about 1000 steps/second can be overcome by slewing rapidly through this region. Careful attention must also be paid to low frequency resonances which can arise at very low stepping rates (100–200 steps/second). At these speeds, a small region can be encountered where the motor will run correctly only if load torque is sufficient.

In practice, the control logic (Sigma Model DMC-10 Preset Indexer) attains precise control of pulse frequency. This system segment allows remote control of four most important performance parameters, i.e., rate, distance, start, stop. The controller accepts remote commands directly from computers, thumbwheels, tape readers, etc. Input logic can be contact closures, TTL or high threshold solid state circuits. The controller contains the



Sigma Model 29B Stepping Motor Translator.

necessary ramping circuits to accelerate high performance motors to rates up to 9,990 steps per second.

The stepping motor driver (Sigma Model 29B Translator) provides the current necessary in the appropriate motor windings to achieve the maximum in speed and torque. The device accepts pulses from the controller.

High Inertia-Low Torque Precision Positioning of Optical Code Disk
A general class of stepping motor system problem is represented by the case where a load of appreciable inertia but low frictional torque is to be positioned precisely upon command. A typical example of this type of problem is the movement of an optical code disk in an electronic typesetting system. In this case, the inertial load represented by the disk must be positioned rapidly and accurately. High stepping rates, rapid damping, and extreme accuracy characterize this application. In order to obtain the

Sigma Model DMC-10 Preset Indexer.

highest possible accuracy, it may be possible to utilize the fact that certain small position errors in a stepping motor tend to be cyclic in nature, as a function of step number. For instance, in a Sigma Series 20 motor, the internal design is such that small errors in position tend to be repeated every four steps. If this type of motor is used with logic that commands steps only in multiples of four, the angular error can be reduced to as little as 1 to 2 minutes of arc. Another interesting consideration when the highest angular accuracy is desired is the torque available from the motor. In general, the greater the available torque, the higher the angular accuracy. This is true because the accuracy is limited by the ratio of the motor stiffness to system torque, as discussed previously. Even in cases where external torque is nonexistent, the motor bearings have a small amount of friction. This factor does not increase rapidly with motor size, so that larger motors tend to exhibit better angular accuracy than small motors. This is particularly true if increased motor torque is achieved by lengthening the motor, which is the desirable method to obtain increased torque in a system designed for high speed. This consideration of high available torque also points out the desirability of bipolar drive in this type of system, since bipolar drive allows increased torque (and motor stiffness) for a given motor power.

The requirement of rapid motion, followed by quick settling, is encountered very often in stepping motor systems. This sequence presents particular difficulty if the load is strictly inertial, and so does not inherently damp system oscillation. The required damping, with a constant inertial load, can be achieved frequently with reverse pulse damping on the last pulse in a train. Another possibility is the use of a constant current driver, and a pulse train spaced so that the final pulses are at a low effective repetition rate. With this scheme, the driver voltage will be low as the repetition rate decreases, and consequently the kinetic energy input to the system will be lowered. Regardless of the drive method employed, it is necessary to examine carefully the system response if small numbers of pulses are to be commanded. As previously discussed, the variation in rotor lag angle with the number of pulses in a batch can have a significant effect on the highest start-stop rate attainable.

Valve Control Servo

A high torque (900 oz-in) synchronous motor is used as a reversible servo motor to continuously control the position of a valve. A differential amplifier receives the valve position feedback potentiometer signal and compares it to the required valve position setting. The output of the differential amplifier switches either the clockwise or counterclockwise triac to drive the motor as shown in Figure 64. The motor power is from the 60 Hz, 120 volt line with no intermediate power supply required. The slow speed (72 RPM) and high torque are achieved without gearing. The motor can stall indefinitely without overheating. Damage to any mechanical equipment is prevented because the stall torque for this type of motor is only slightly higher than the running torque.

Pen Positioning on Chart Recorder

Chart recorder pens represent a very light load and require a small low-cost, permanent magnet, synchronous motor with 1–5 oz-in of torque for posi-

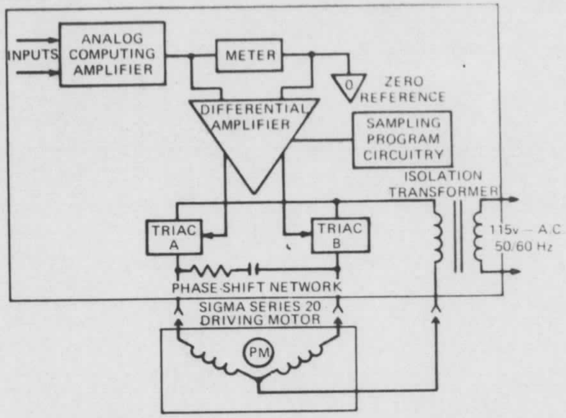


Figure 64. Valve Control Servo.

tioning. The analog input signal and the pen position feedback potentiometer signal are the inputs to the differential amplifier. The amplifier output controls either of two Sigma Ladybug® optical couplers to directly drive the motor in the required direction. The very low-cost Ladybug® couplers represent an economical means of isolating the AC motor from the differential amplifier.

Pump Speed Control

It is necessary to operate a blood pump accurately under control of a small computer under surgical conditions. Since the required speed rate is constantly varying, it is computed digitally with the pulse train fed directly from the computer to the stepping motor for direct control. This application takes advantage of the inherent capability of the stepping motor to lock onto a digital pulse train with absolute accuracy over a very wide range of speeds independent of load variations with no feedback. Conventional speed control using DC brush motors with back EMF feedback control may have a range of 20:1 below 1750 RPM with accuracy ±3% of top speed and regulation ±5% of top speed. Only the absolute accuracy obtainable from the stepping motor at the low speeds of from 0 RPM to 1300 RPM without gearing – and at no extra cost – is acceptable in this application. In addition, since the speed of the stepping motor is independent of load variations, the accuracy of the computer controlled speed is assured even though the load is constantly changing. Although not a part of this application, the motors can be employed in follower drive systems for process and machine control applications where several motors are required to run in absolute synchronism without any slip during start up or load change. This again takes advantage of the "lock-on" characteristics of these motors for speed control.

Automatic Sorting of Parts

Parts (in this case, reed switches) are manufactured in high volume by a process which inherently produces a certain scatter in characteristics, as well as a percentage of unuseable switches. In this automatic device, a

stepping motor system is used as an integral part of the tester. A reed switch under test is automatically checked for various defects (high contact resistance, slow pick-up time, etc.). If these tests are passed, a staircase of current is applied to the test coil to determine the sensitivity of the switch (ampere turn rating). The motor is stepped synchronously with the staircase, so that the output chute is positioned at the bin which corresponds to the current valve in the coil at all times. When switch closure is achieved, the system is stopped and the switch is automatically dropped in the appropriate bin. If a switch is rejected for any reason, the system positions the chute to a bin labeled with the reason for rejection.

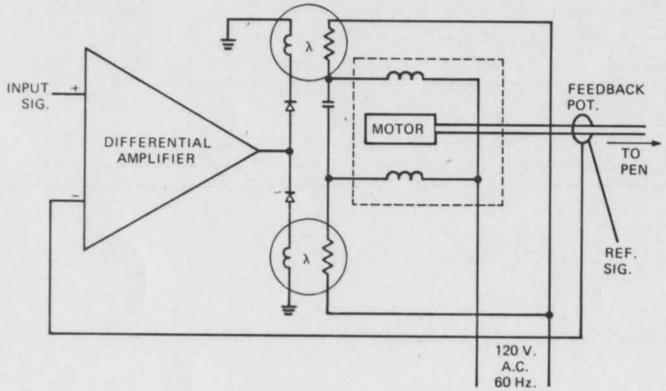


Figure 65. Control Circuiting for Chart Pen Positioning.

NOTES

ROTARY INERTIA CONVERSION TABLE

To convert from A to B, multiply by entry in Table.

A \ B	gm-cm^2	oz-in^2	gm-cm-sec^2	Kg-cm^2	lb-in^2	oz-in-sec^2	lb-ft^2	Kg-cm-sec^2	lb-in-sec^2	lb-ft-sec^2 or slug-ft^2
gm-cm^2	1	5.46745×10^{-3}	1.01972×10^{-3}	10^{-3}	3.41716×10^{-4}	1.41612×10^{-5}	2.37303×10^{-6}	1.01972×10^{-6}	8.85073×10^{-7}	7.37561×10^{-8}
oz-in^2	182.901	1	0.186507	0.182901	0.0625	2.59009×10^{-3}	4.34028×10^{-4}	1.86507×10^{-4}	1.61880×10^{-4}	1.34900×10^{-5}
gm-cm-sec^2	980.665	5.36174	1	0.980665	0.335109	1.38874×10^{-2}	2.32714×10^{-3}	10^{-3}	8.67960×10^{-4}	7.23300×10^{-5}
Kg-cm^2	1000	5.46745	1.01972	1	0.341716	1.41612×10^{-2}	2.37303×10^{-3}	1.01972×10^{-3}	8.85073×10^{-4}	7.37561×10^{-5}
lb-in^2	2.92641×10^{3}	16	2.98411	2.92641	1	4.14414×10^{-2}	6.94444×10^{-3}	2.98411×10^{-3}	2.59009×10^{-3}	2.15840×10^{-4}
oz-in-sec^2	7.06157×10^{4}	386.088	72.0079	70.6157	24.1305	1	0.107573	7.20079×10^{-2}	6.25×10^{-2}	5.20833×10^{-3}
lb-ft^2	4.21403×10^{5}	2304	429.711	421.403	144	5.96756	1	0.429711	0.372972	3.10810×10^{-2}
Kg-cm-sec^2	9.80665×10^{5}	5.36174×10^{3}	1000	980.665	335.109	13.8874	2.32714	1	0.867960	7.23300×10^{-2}
lb-in-sec^2	1.12985×10^{6}	6.17740×10^{3}	1.15213×10^{3}	1.12985×10^{3}	386.088	16	2.68117	1.15213	1	8.33333×10^{-2}
lb-ft-sec^2 or slug ft^2	1.35582×10^{7}	7.41289×10^{4}	1.38255×10^{4}	1.35582×10^{4}	4.03305×10^{3}	192	32.1740	13.8255	12	1

TORQUE CONVERSION TABLE

For Units Required, Multiply by Factors Below

Given Units	dyne-cm	newton-meters	oz-in	ft-lbs	in-lbs	gm-cm
dyne-cm	1	10^{-7}	1.41612×10^{-5}	7.37562×10^{-8}	8.85074×10^{-7}	1.01972×10^{-3}
newton-meters	10^{7}	1	1.41612×10^{2}	7.37562×10^{-1}	8.85074	1.01972×10^{4}
oz-in	7.06156×10^{4}	7.06156×10^{-3}	1	5.20833×10^{-3}	6.250×10^{-2}	7.20075×10
ft-lbs	1.35582×10^{7}	1.35582	192	1	12	1.38255×10^{4}
in-lbs	1.12985×10^{6}	1.12985×10^{-1}	16	8.33333×10^{-2}	1	1.15212×10^{3}
gm-cm	9.80665×10^{2}	9.80665×10^{-5}	1.38874×10^{-2}	7.23300×10^{-3}	8.67961×10^{-4}	1

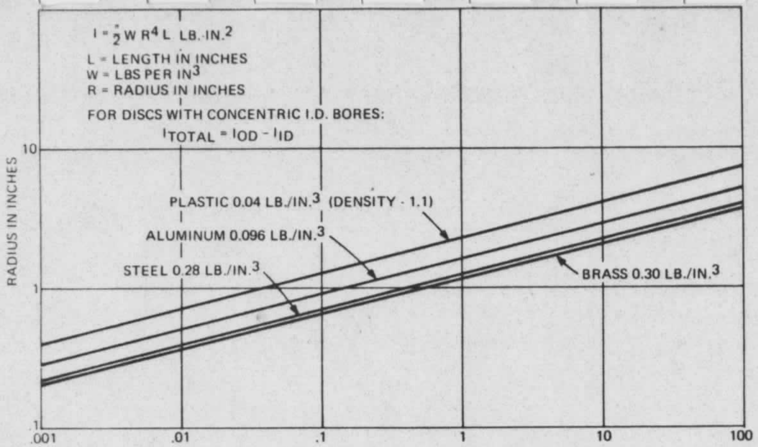


Figure 66. Polar Moment of Inertia of Circular Cylinder.

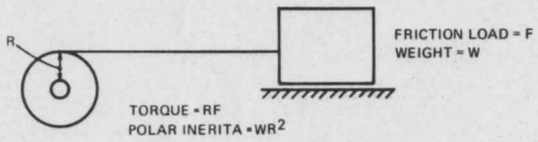
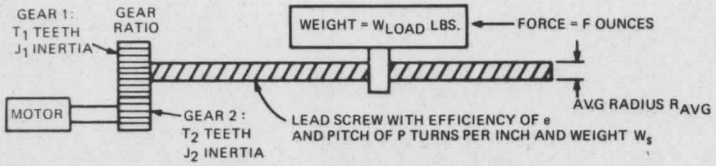


Figure 67. Load Operating at a Radius.



AT MOTOR SHAFT:

$$\text{TORQUE} = \frac{F}{2\pi P e}\left(\frac{T_2}{T_1}\right) \text{ OZ.-IN.}$$

$$J_{LOAD} = \frac{W_{LOAD}}{(2\pi P)^2}\left(\frac{T_2}{T_1}\right)^2 \text{ LB. IN.}^2$$

$$J_{\substack{LEAD\\SCREW}} = 1/2\, W_s R_{AVG}^2 \left(\frac{T_2}{T_1}\right)^2$$

$$J_{GEAR_2} = J_1 \left(\frac{T_2}{T_1}\right)^2$$

$$\text{TOTAL INERTIA} = J_{MOTOR} + J_2 + J_1\left(\frac{T_2}{T_1}\right)^2 + 1/2\, W_s R_{AVG}^2\left(\frac{T_2}{T_1}\right)^2 + \frac{W_{LOAD}}{(2\pi P)^2}\left(\frac{T_2}{T_1}\right)^2$$

Figure 68. Loads Operating Through Lead Screws.

To find output speed in RPM or RPS, find appropriate values for Steps/Revolution and Steps/Second. Extended straight line across these points will indicate correct RPM/RPS value at intersection.

For example: 100 Steps/Revolution at 1000 Steps/Second gives 600 RPM (or 10 RPS).

To find output power in horsepower and watts, find appropriate values for RPM/RPS and OZ-IN/GM CM. Straight line between these two points will intersect at correct output power value. For example: 100 revolutions per minute at 400 oz-in torque provides slightly over 30 watts.

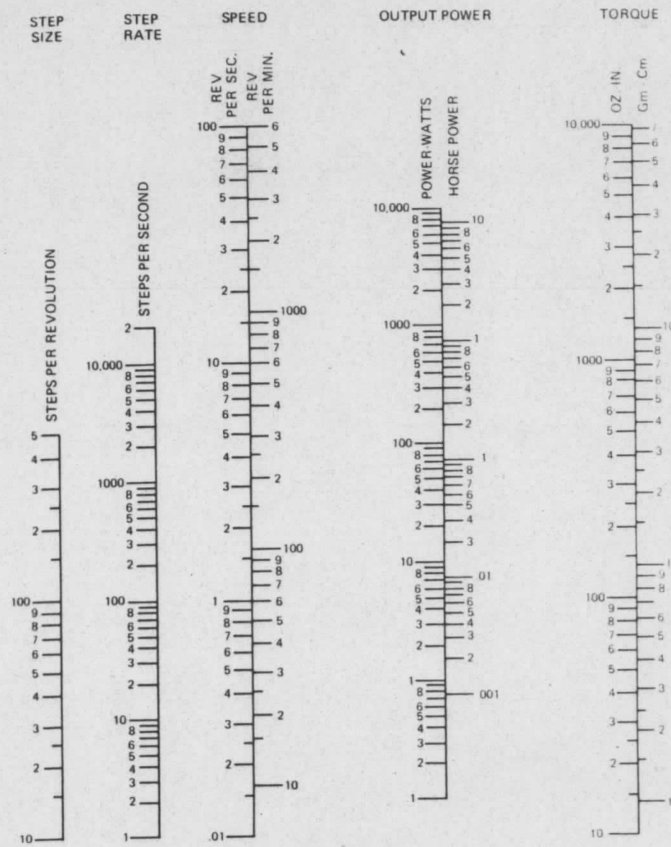


Figure 69. Angle – Speed – Power.